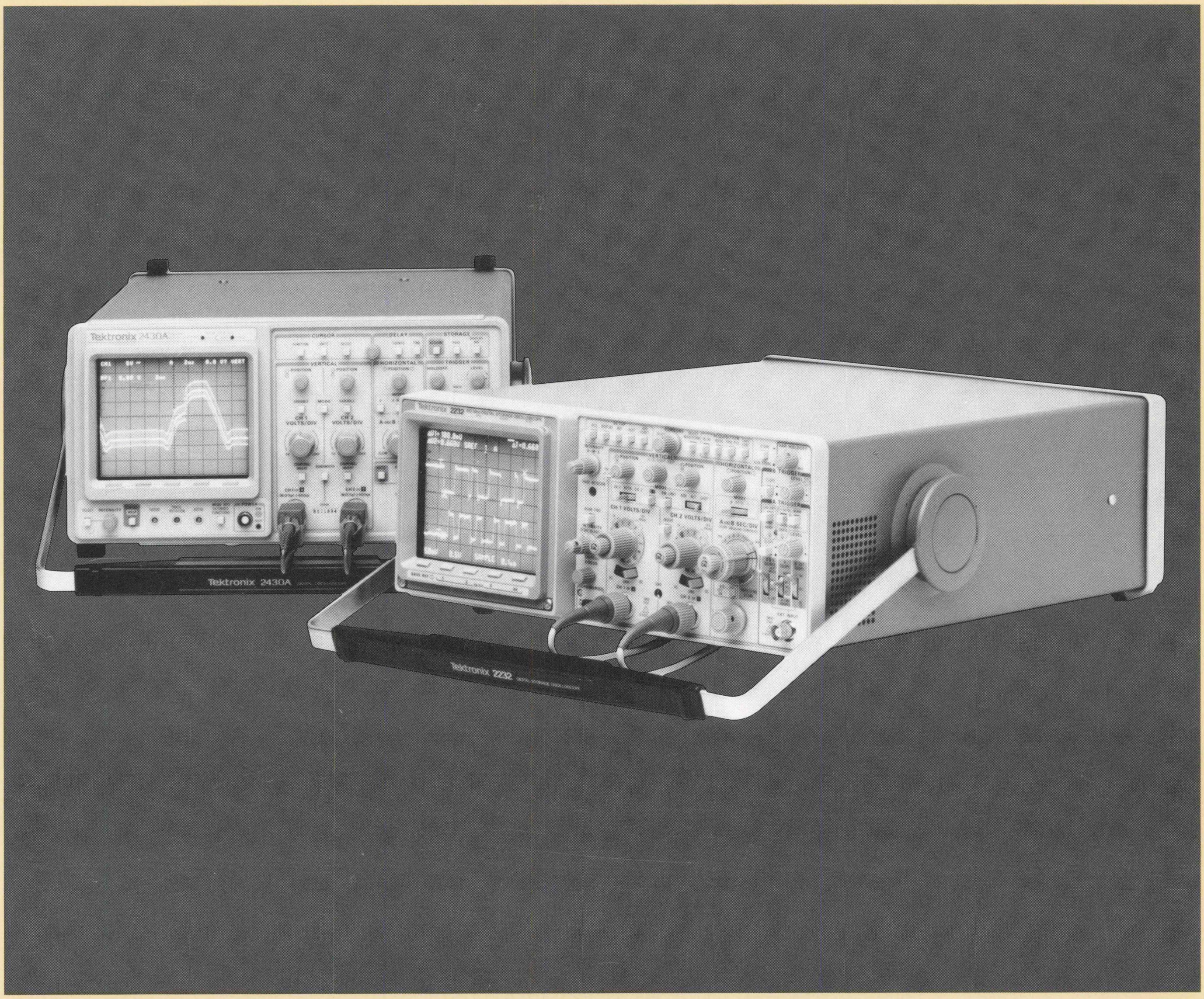
AN INTRODUCTION TO DIGITAL STORAGE



Tektronix
Test and Measurement

TABLE OF CONTENTS

PREFACE

To some, the words "analog to digital conversion" mean the inevitable replacement of every analog system and device with a digital unit.

This simply isn't the case—not when you consider that analog to digital conversion has always been practiced, it being the representation of physical parameters by numbers. When you measure the height of a door with a ruler, for example, or tell time with a watch, you are performing analog to digital conversions. The same goes for measuring a waveform against an oscilloscope graticule.

In the interests of accuracy, productivity and efficiency, mankind has produced an amazing variety of analog to digital converters. These are really automatic measurement devices. Odometers, gasoline pump meters, radar, digital potentiometer dials, digital voltmeters, frequency counters, time interval counters and waveform digitizers—all incorporate analog to digital converters.

A waveform digitizer is one such universal device. It quantizes all features of a signal, both in time and in amplitude. It generates a list of numbers that represents the amplitudes of closely spaced, accurately timed waveform samples. The list of numbers can be interpreted to determine the amplitude, repetition rate, transition times, duty factor, frequency spectrum, rms voltage and other characteristics of a signal. By sampling two or more signals concurrently, the waveform digitizer generates data that implies time skew or phase difference—among a host of possibilities.

This primer, hopefully, will help you make the correct decision for your particular storage needs. With the likes of the newer digital storage oscilloscopes from Tektronix such as the 336, 2220, 2230, 2430, 7D20, 7854, 5D10 and 5223 you may find that the universal solution is getting close to just that.

WHY STORE?

You may be aware of many reasons why we need to store waveforms, but let's list a few of them just to illustrate how digital storage can be of advantage.

Primary reasons include: the need to see "single shot events;" stopping low-rep rate "flicker;" observing changes during circuit adjustment; comparing incoming signals with standard; unattended monitoring for transient events; and in some cases, record keeping. Conventional scopes in general do not have the ability to retain these types of signals on screen for very long, if at all. In fact, most of these signals cannot conveniently be seen on conventional oscilloscopes. The only way to record them is to take a waveform photograph; of course, this is also a form of storage. But this is a very cumbersome and, in the long run, very expensive method when you consider the amount of time and film spent. CRT storage, on the other hand, greatly reduces the amount of time and film required; the trade-off, however, is the up front cost. As you will find, a digital storage oscilloscope (DSO) can make most of the measurements you require, in addition to offering many more possibilities.

CONVENTIONAL STORAGE

It is appropriate to mention "conventional" analog methods of oscilloscope storage in order to understand the advantages of digital storage and even the advantages of conventional analog storage. Yes, there are still some advantages to analog storage, although they are decreasing rapidly with new analog-to-digital-converter and display technology.

Phosphor (Bistable)

Bistable storage was the first oscilloscope storage available. Bistable CRT storage uses a special phosphor with two stable states: written and unwritten.

Bistable storage is probably the easiest to use and the least expensive CRT storage; however, as far as writing speed is concerned, it offers the least performance. The principal applications for this type of storage are in mechanical applications, signal comparisons and data recording. Most bistable CRTs have split screen capabilities, i.e., the ability to store signals on one half the screen independent of what is on the other half. This unique advantage of bistable storage provides the ability to display a known waveform while viewing other waveforms that you may want to compare. However, this can also be done very easily and more effectively with newer digital storage oscilloscopes, such as the Tektronix 2220 and 2230, and at a much better performance/price ratio.

It would seem that bistable storage may be going the way of the dinosaur. There are, however, a couple of areas in which bistable storage still has a performance/price advantage: these being the need to display a large number of waveforms on the screen and, second, vertical resolution requirements. Resolution will be discussed later in this document. The main disadvantages to this type of storage are the ability to reposition waveforms once they have been captured and display quality achieved in terms of brightness and contrast, especially when compared to digital storage's clean, crisp displays.

MESH STORAGE

There are essentially two types of mesh storage: variable persistence and fast transfer.

Variable Persistence. Just as the name implies, variable persistence has the ability to vary the persistence of the signal or vary the amount of time that the signal is displayed on the CRT. We can adjust the decay time so that the beginning of the signal will start to fade just as a new sweep starts or, for that matter, at any point we choose—even to the point of displaying several waveforms so that you may see the response an adjustment may have in a circuit. This type of CRT storage also gives you the ability to integrate a waveform so that only coincident portions of a waveform are displayed, essentially averaging the waveform. Some bistable storage scopes also have this capability, as do the newer Tek digital storage oscilloscopes, the 2220, 2230 and 2430. Usually there is a "save" feature that allows you to save a waveform to use as a comparison to other waveforms. Variable persistence's main advantage is its ability to display low-repetition rate, fast risetime signals to the capabilities or bandwidth of the particular oscilloscope. Again, with newer Tektronix oscilloscopes, the 2220, 2230 and 2430, a similar capability is available. This is sometimes called equivalent time sampling, but more about that later. Variable persistence usually has good contrast between the signal and the background when compared to other CRT storage.

Fast Transfer. Storage of this type uses a CRT with a special intermediate mesh target which is optimized for speed. The target mesh captures the waveform and transfers it to a storage mesh. The second target can be designed to offer bistable or variable persistence modes as in the Tek 7633, which offers all three modes, or the Tek 466, which is optimized for speed and variable persistence. Fast transfer storage is still the performance leader for high-speed, single-shot events. Although digital storage is gaining significantly in this area, there is still a significant cost-to-performance advantage in favor of the CRT mesh storage oscilloscope. The main disadvantage of this type of CRT storage is the brief time that the signal is available to view or record with a camera. This is especially true when the upper limit of the storage capability is reached. This is not the case for digital storage; once the signal is captured, your view time is "unlimited."

INTRODUCTION TO DIGITAL STORAGE

The fundamental difference between the digital storage scope and its analog counterparts is the form of storage. Digital scopes store data representing waveforms in a digital memory; analog storage scopes store waveforms within the CRT as shown in Figure 1.

Digital storage requires digitizing and reconstruction processes. Digitizing consists of "sampling" and "quantizing." Sampling is the process of obtaining the value of an input signal at discrete points in time; quantizing is the transformation of that value into a binary number by the ADC in the digital scope. You determine how often digitizing occurs by the "time base." The time base in the digital storage scope consists of a digital clock as opposed to the "sawtooth" or linear voltage ramp that is used in conventional oscilloscopes. This clock gives discrete points in time to reference our quantized values of the input signal, then the information is stored in some form of digital memory. The rate at which this clock "ticks" is called the digitizing rate and is usually specified in mega-samples per second (MS/s) or points per second. Once the data is in the digital memory, it can be read out and displayed on the CRT, further processed or transferred to a computer—among many possibilities.

RESOLUTION AND ACCURACY

A few basic terms need to be defined in order to become more familiar with and better understand digital storage, how it operates, how it relates to CRT storage and how it is specified.

Accuracy and Resolution

Webster defines resolution as the "...capability of making distinguishable the different parts of an object...," while accuracy is defined as "conformity to truth or to a standard or to a model." These two concepts are extremely important since they are often confused by some manufacturers of competitive Digital Storage Oscilloscopes (DSOs).

Both resolution and accuracy are critical in a measurement instrument. A user needs to know how "accurate" a measurement is; but in order to "measure" this, one must "resolve" differences to a finer degree than the accuracy. Thus before "accuracy" can be obtained, one must have resolution. Since the measurements are made against a graticule, we must consider a third parameter, linearity; i.e., the observed deflection must be linearly related to the unknown input.

In other words, "reasonable" resolution is required before measuring linearity. In turn, one must have "reasonable" linearity in order to obtain accurate measurements.

The terms "accuracy" and "resolution" are not synonymous. Resolution is the distinguishing of individual items while accuracy is "the conformity of an indicated value with a true or accepted standard value." To picture the difference, imagine a scale with a 3-digit readout. When you step on it, the display reads 150 pounds. The register weight could have been anything from about 149½ pounds to about 150½ pounds. So the resolution of this scale is 1 pound, the smallest unit that can be distinguished.

But what is the accuracy of the scale? Imagine getting an official 150-pound weight from the Bureau of Standards. When you put the weight on the scale, the readout said 147 pounds. Now you know that the accuracy of the scale is 2% (3 divided by 150), at 150 pounds. Accuracy, however, is always specified for the full range of possible measurements and maybe this scale is accurate within 15% over its entire range of 1 to 999 pounds.

Note that your measurements cannot be more accurate than the scale's resolution; that is why resolution is an important specification for a measurement instrument, either scale or scope. Another equally important reason is that resolution determines your ability to see fine detail or small changes in your measurement. If you were dieting, for example, you would be interested whenever the scale showed that you had lost a pound. In this case, you are less interested in the scale's accuracy than you are in its resolution.

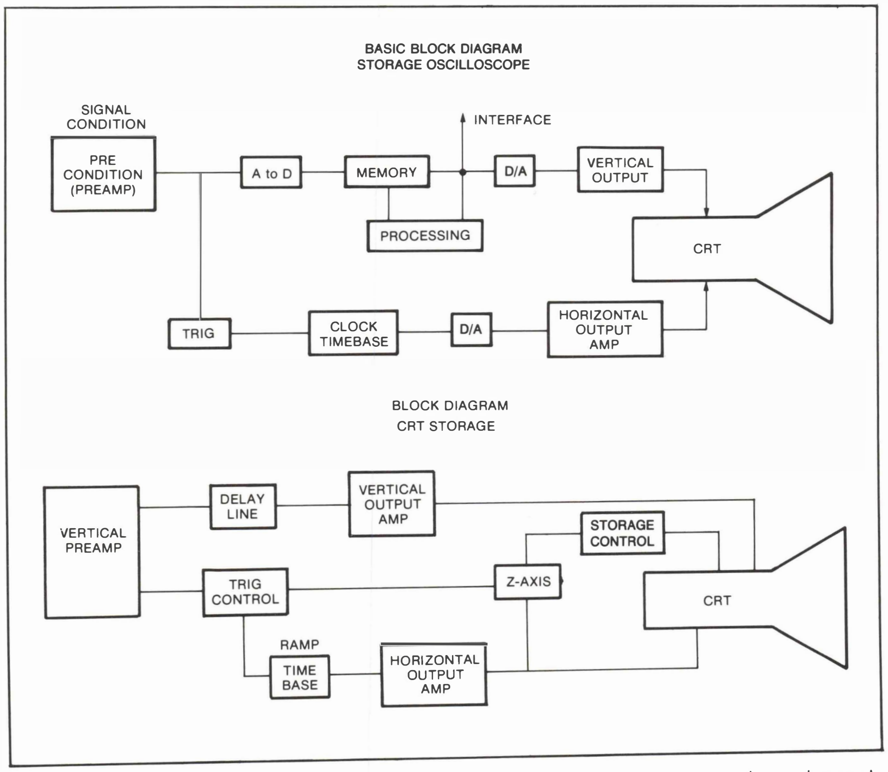


Figure 1. Basic block diagram shows the two types of storage. In CRT storage the major cost difference over a conventional analog scope is the CRT, with some added cost for the CRT control circuits (highlighted). In digital storage, the major cost difference is the analog to digital converter (ADC) and its support circuits (highlighted). As the cost of ADCs decreases and performance increases, CRT storage has less cost advantage.

Resolution of Conventional Storage

The resolution possible on the CRT of an analog scope is a function of the screen size and the electron beam spot size and shape. Usually CRTs are 8 divisions high by 10 divisions wide and are measured in centimeters. Typically, spot size ranges from 1/25 to 1/50 of a division and can resolve half a trace width; therefore, the vertical resolution is 1 part in 400 to 1 part in 800, while the horizontal resolution is 1 part in 500 to 1 part in 1000.

Resolution of Digital Storage

As we mentioned in the "Introduction to Digital Storage," digital storage requires digitizing and reconstruction processes. "Digitizing" consists of "sampling" and "quantizing." Sampling is the process of obtaining the value of an input signal at discrete points in time; quantizing is the transformation of that value into a binary number by the analog to digital converter (ADC) in the digital scope. You determine how often digitizing occurs by using the switch on the time base. The time base uses a very precise digital clock to time the analog to digital (A/D) conversion and to store the data in memory. The rate at which this happens is the digitizing rate (or sampling rate). Once the data is in the digital memory, it can be read out at a fixed rate and reconstructed for display.

The ADC takes a voltage somewhere in the continuous range of possible voltages and outputs a number to represent it. The input voltage may have any value within the converter's range (3, 4, 3.5, 3.5163 volts, etc.), but the ADC can only discriminate between values to the limit of its resolution. So every quantized voltage output by the ADC is an approximation for a subrange of possible analog values. It is the size of the subrange that is important to you when you make voltage measurements. This size is the resolution of the ADC, and it is determined by the number of bits in the binary number used to represent the analog input.

An ADC that outputs a 2-bit binary number ("bit" is from binary digit) can only represent four subranges; for a full scale of 0-10 volts, the subranges are 0-2½, 2½-5, 5-7½, and 7½-10 volts. With more bits the full scale is further subdivided, and the minimum subrange expressed is smaller. So the more bits used to express the input voltage, the better

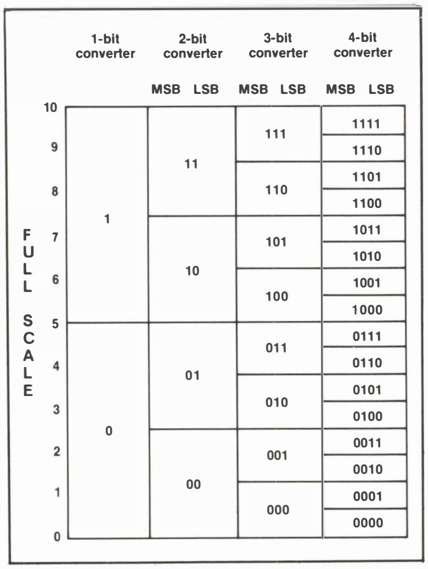


Figure 3. Four A/D converters are shown subdividing a full scale range of 0 to 10 volts. Each bit the ADC uses represents an equal sized subrange of analog values, so these are called "quantizing units." The "weight" of the LSB for each of the converters can easily be seen in the drawing as the size of the quantizing units decreases with the addition of bits.

the resolution of your measurements.

Two of the bits in the binary output of an ADC have names. The first digit is the most significant bit—the MSB —and the last digit is the least significant bit - the LSB. The LSB expresses the smallest subrange the ADC is capable of resolving. This is the "weight" of the LSB, and it tells you how accurate your voltage measurements can be with that particular ADC. For example, in the 4-bit converter diagrammed in Figure 3, the weight of the LSB is 0.625V (10V times 1/16). The weight of the LSB tells you how accurate your measurements can be ideally, but that is not a guarantee. The accuracy is dependent on more than just the resolution of the ADC, as you will see later.

In digital storage, resolution depends on the number of bits used by the converter, "bits of resolution of 1 part in 2^n or n bit resolution" where "n" is the number of bits. Sometimes ADCs are described as having "2^n levels of resolution;" this is the number of elements or items that can be distinguished with that converter. You can translate levels back to bits of resolution with Table 1. The table also lists expressions of resolution in the equivalent percentage and in parts per million. From the table you can see that it doesn't take many bits to get good resolution.

While the horizontal resolution in CRT storage is determined by the CRT, digital storage is determined by the number of time increments that you store (memory) and can measure between. With 1024 bits the resolution would nominally be better than most CRT storage scopes. However, if you use a digital scope to just write the data on the screen once (as opposed to using the averaging feature described later) and you choose not to use cursors and expansion, then the accuracy of your timing measurements will be limited by the screen resolution of the scope. Figure 3A compares possible DSO resolution to CRT resolution.

Table 1. Expressions of Resolution

BITS	PERCENTAGE	PPM	LEVELS
1	50%	500,000	2
2	25%	250,000	4
3	12.5%	125,000	8
4	6.25%	62,500	16
5	3.125%	31,250	32
6	1.563%	15,625	64
7	0.781%	7,812	128
8	0.391%	3,906	256
9	0.195%	1,953	512
10	0.098%	977	1024
11	0.049%	488	2048
12	0.024%	244	4096
13	0.012%	122	8192
14	0.006%	61	16,384
15	0.003%	31	32,768
16	0.0015%	15	65,536
17	0.0008%	7.6	131,072
18	0.0004%	3.8	262,144
19	0.0002%	1.9	524,288
20	0.0001%	.95	1,048,576

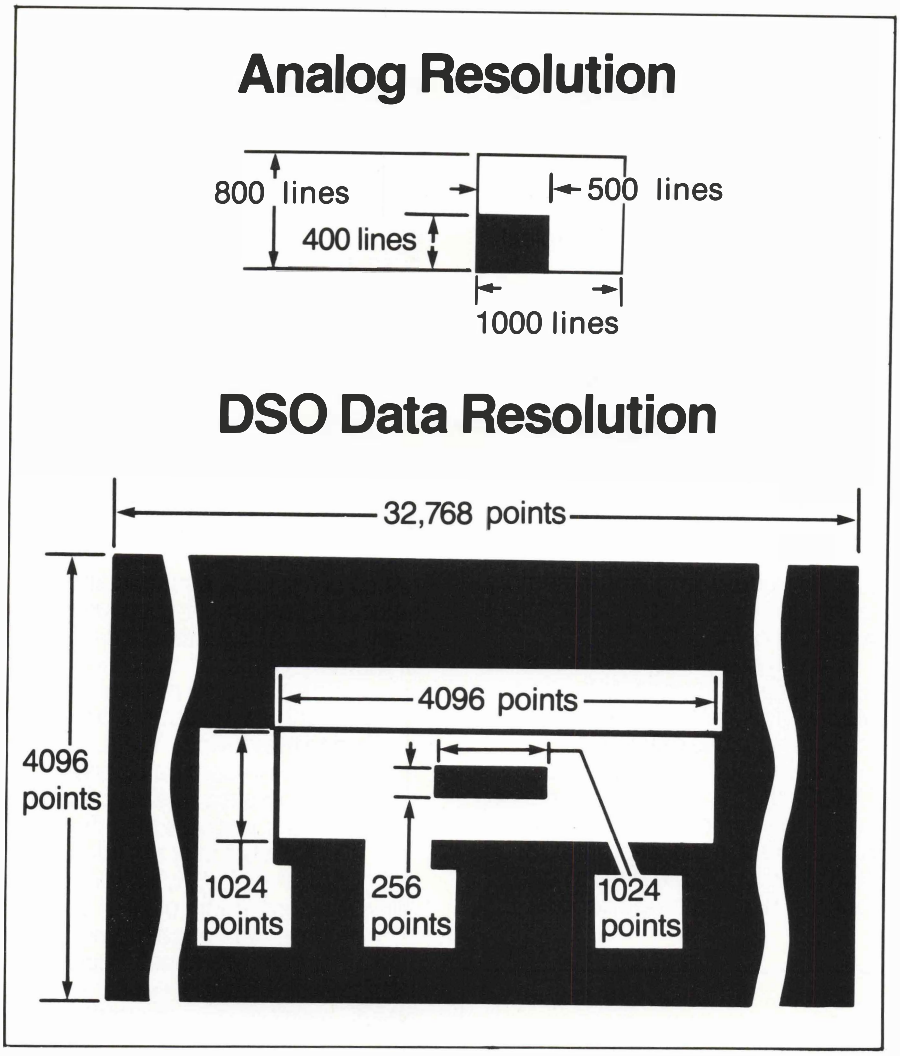


Figure 3A. The comparative resolution of digital and analog resolution is depicted above. On the horizontal axis, the maximum CRT resolution would be about 10 bits $2^{10} = 1024$: on digital storage it would be limited by the record length (memory). Some DSOs may have as much as 32,768 bits; but in general, 4,096 is the standard on medium performance instruments. Many factors limit horizontal resolution in DSOs, and some of these are explained later. On the vertical axis the maximum resolution in the CRT is about 800 bits and on DSOs it is limited by the ADC. Most are 8-bit converters or 256 points of data. More bits are available at a higher cost, and this is a trade-off that must be made in the selection of a DSO. The highest resolution ADC readily available is 12 bits, but the sample rate is generally much lower on these ADCs, another trade-off. In general, the vertical resolution is better in CRT storage with a minimum 400 bits of information resolvable, but the technique of averaging will swing the pendulum back to DSO. There will be more on averaging later.

Accuracy

Accuracy of a CRT storage scope is limited vertically by the sum of vertical amplifiers and the CRT (linearity resolution, etc.) and usually this may vary from 2-4%. Horizontally it is the linearitv and horizontal amplifiers plus the CRT that make up the accuracy of the horizontal. These are usually on the order of 1-3% accurate.

Accuracy in a digital storage scope will have different characteristics than an analog scope. With the difference between resolution and accuracy in mind, you can see that the vertical resolution of a digital storage scope is simply the ADC's resolution, but the accuracy is a different matter. Accuracy depends on more than the resolution; it also depends on the linearity and accurracy of the input and output amplifiers, which are just like those used in analog scopes. As a consequence, the possible accuracy implied by the ADC resolution (0.391% for an 8-bit converter; 0.098% for 10 bits) will not be the accuracy of your measurements. Instead, you will usually find the same accuracy specifications as in analog scopes: vertically 2-4% and horizontally 1-3%.

But with digital storage you will gain accuracy from using cursors; they improve the repeatability of your measurements by reducing human errors and the effects of CRT and amplifier nonlinearities.

Digital Time Bases Accuracy

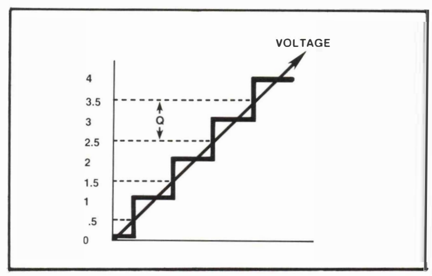
The clock used by a digital storage scope is usually a crystal oscillator of an established frequency. An analog scope uses a ramp to generate the time base and will usually be specified at 1-3% accuracy. The digital clock is so precise, however, that greater than 0.01% is possible. More importantly, the digital clock offers superior stability, and because the digital time base is derived by counting cycles —not from an analog ramp—the linearity is better by orders of magnitude.

Because you are displaying the signal on the CRT, you will again, as in the vertical, be limited by the accuracy of the display. But you can use expansion and cursors to take advantage of the digital time base accuracy. With the cursors, the accuracy is limited by either the clock accuracy, the data memory length or cursor resolution and accuracy—whichever is worse.

Quantizing

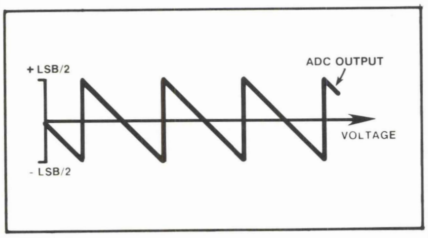
We have discussed resolution and accuracy and described how these parameters are derived, but one important consideration has not yet been addressed.

How bits are assigned to the analog value of the sampled points is called "quantizing." We must "quantize" each of these points that our digital time base specifies. This diagram demonstrates basic quantizing theory:



As the analog voltage (black line) increases, it crosses transitions or "decision levels" (dotted blue lines), which causes the ADC to change states as represented by the solid blue line. This is the process of quantizing. In an ideal ADC represented by the drawing, the transitions are at half unit levels and Q represents the distance between decision levels, also called the "bit size" or "quantization size." Even in the theoretical ADC there is always a "quantization uncertainty" because, though Q may

be very small, it is still a finite range and any analog value within that range can be present. The quantization uncertainty is expressed as plus or minus LSB. Another way of looking at this uncertainty is in this drawing.



As the plot of the quantizing error shows, the output of an ADC may be thought of as the analog signal plus some quantizing noise. The more bits in the ADC, the less significant the noise is.

This is all theoretical because in the real world the decision levels are not firm lines, but are bands, and an analog value within one of those bands could be translated to either of two discrete outputs. Actual ADCs might also have different Q distances between the decision levels because of errors of non-linearity and gain. In a good ADC none of these errors will add up to more than plus or minus ½ LSB.

Acquisition and Aperture Parameters. There are certain parameters that limit the rate at which an ADC can acquire a sample of the input waveform. These are acquisition turn on delay, acquisition time, sample or track time and hold time. Figure 4 below gives a graphic representation of the acquisition cycle of a typical analog to digital converter.

MEMORY AND RECORD LENGTH

A particular instrument may have the ability to acquire 1024 points per waveform—this would be the "record length." The same instrument may be able to store several waveforms, it may have a memory length of 32K. Record length and memory length are important considerations when choosing a DSO.

Many types of memory, called by many different names, are associated with digital storage, but typically fall into two categories: semiconductor and magnetic. CMOS, NMOS and ECL are classified in the former, while bubble, tape and disk are in the latter. CMOS, NMOS and ECL are likely to be found in digital storage scopes. ECL, best noted for its fast access time, has the drawback of consuming considerable power and is costly compared to CMOS and NMOS.

In the Tek 2430 and 2230, NMOS devices are used even though they are generally more expensive than CMOS, cost always being a consideration in the design of general purpose test instruments. However, the added speed of the NMOS devices is a requirement in both instruments. Another advantage of NMOS and CMOS is their relatively high memory capacity. In fact, the 2230 has, along with its 8k of internal waveform memory (4k of acquire and 4k of reference), 26k of optional battery-backed static CMOS memory for long term storage of waveforms.

CMOS and NMOS have two categories of memory: dynamic and static. Dynamic must continually be "refreshed" in order to retain its state or memory. Static, on the other hand, once addressed, will maintain that state as long as the correct power is applied to the device. Again, there are trade-offs in both categories. Dynamic is less expensive, has more density and consumes less power. This was the choice of the internal memory in the 2230, which helped to allow a record length of 4k of acquisition and 4k of reference memory. The 2430, not being so constrained by cost, power or space, uses the static NMOS memory; thus the 2430 is able to offer waveform retention in the internal memory for several days, using a large capacitor as a power source for the memory devices.

We have discussed random-access memory, or RAM, which is used to store variables that digital storage scopes acquire and display. Another form of memory sometimes used in storage scopes is Read Only Memory, or ROM. This is a permanent memory in which the instrument operating system, display characters (if available), processing algorithms and other internal code that the instrument requires are stored.

Usually, external to the instrument we may find access to forms of magnetic memory such as floppy disk, hard disk, magnetic tape and, in some cases, bubble memory (this is probably the most expensive form of the magnetic media). The magnetic media is usually used as a form of mass storage and is usually accessed via GPIB or RS-232-C through a controller which may be a

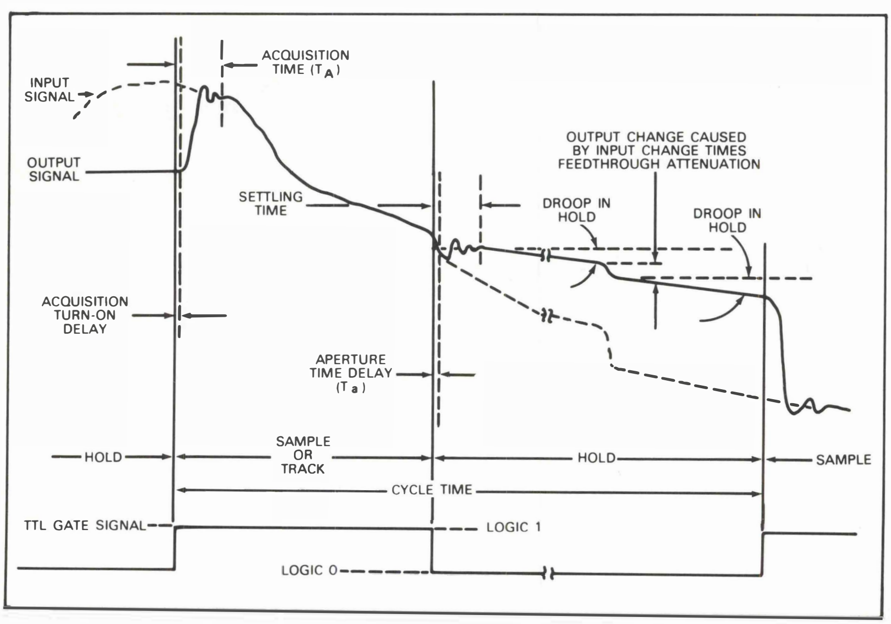


Figure 4. The above illustration shows the elements that make up the acquisition cycle of an ADC. The turn on time or the time that the device takes to get ready to acquire a sample is the first event that must happen. The acquisition time is the next event that occurs. This is time that the device takes to get to the point at which the output tracks the input sample, after the sample command or clock pulse. The aperture time delay is the next occurrence. This is the time that elapses between the hold command and the point at which the sampling switch is completely open. The device then completes the hold cycle and the next acquisition is taken.

4041, PC or other such device. The Tek 2430, 2230, 2220, 7D20 and 7854 all have the ability to address the magnetic media in some form.

It may seem that almost any length of memory is possible to achieve internally with today's memory technology. However, there are other factors that enter into the design of digital storage oscilloscope besides real estate, speed and cost.

Update rate is one such factor. The longer the memory, the longer it takes to acquire a record and the longer it takes to refresh the display. When purchasing a general purpose DSO, one should consider how the instrument responds compared to any other type of oscilloscope. Even though a DSO will never respond the same, the closer the better and refresh time is certainly one aspect. The 2230 is maximized to address the general purpose oscilloscope market, which requires a relatively long record length. All of the above factors were considered in selecting a record length of 4K for the 2230. There are areas that require much longer record length, but there is usually a trade-off in cost, sample rate, etc., to achieve that goal.

Another consideration that will sometimes limit the record length is the type of device that is used to acquire the analog signal; for example, in the Tek 2430 the memory is limited by the CCD (Charge Coupled Device) to 1K per channel. Most of the other CCDs currently being used in digital storage oscilloscopes are only 256 words long. CCDs have the ability to acquire data at sample rates of up to and over 100 megasamples per second at a very modest price—offering the highest performance-to-cost-ratio of any device available today.

ANALOG TO DIGITAL CONVERTERS

There are several methods of digitizing or quantifying the different voltage levels of a waveform. We address three in this document: successive approximation converters, flash converters and scan converters. We will also include one sample and hold technique (charge coupled devices) that enables us to use one of the other methods of A to D to digitize high speed signals.

Successive Approximation Converters

These converters compare the input voltage to the output of a digital to analog converter (D to A). If the input is higher than the D to A output, the MSB (most significant bit) is set high; if it is lower, the MSB is set low. The converter then progresses to the next significant bit. Figure 5 illustrates this hunting process. Successive approximation converters have a fixed conversion time per bit. So, there is a trade-off between conversion speed and resolution (8-bit versus 10-bit). For a high resolution converter, you must accept a relatively long conversion time.

Flash Conversion

Flash Conversion is a technique for converting analog signals to digital output in the shortest period of time. It consists basically of a binary resistive divider and a number of comparators equal to the binary resolution. Figure 6 illustrates the concept.

Although having a short conversion time, the weighted values of the

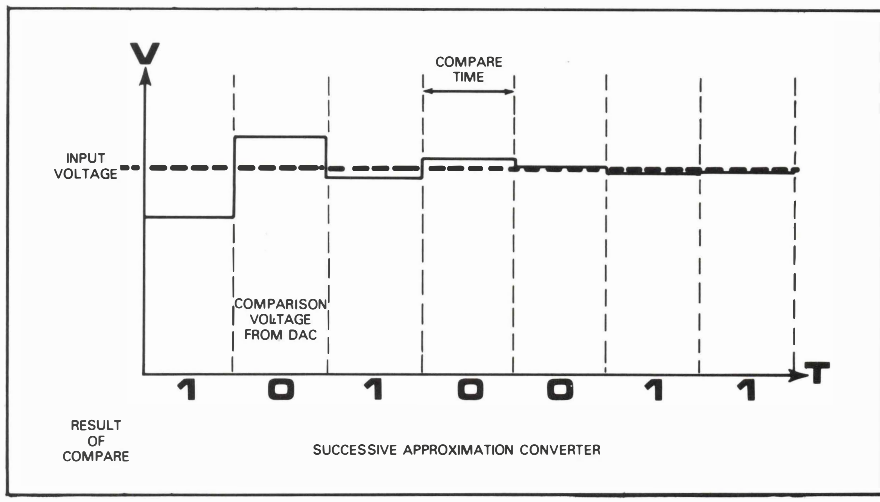
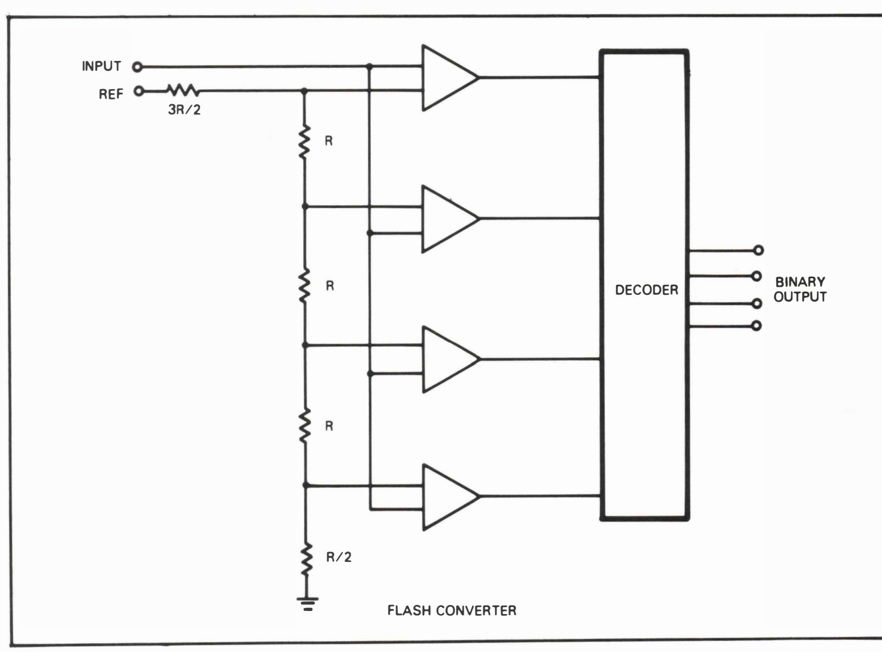


Figure 5. Successive Approximation Converter. Note that the time to convert the analog input to a digital number is directly proportional to the resolution achieved. This is a very popular conversion method, offering medium speed with high accuracy.



resistive divider may degrade as the frequency increases. Care in designing the divider must be taken to compensate for the frequency response.

Charge Coupled Devices (CCD)

We mentioned earlier that we would discuss a device that is really not an analog to digital converter. This is called a charge coupled device (CCD) and is actually an analog sampler. A CCD can sample at a very high rate and convert samples to a much lower rate. A good example is the way in which slow motion pictures are achieved. The film is run through the camera at a much higher rate of speed than normal, correlating to acquisition. Each frame is "stored" (as in the memory section of a CCD) for later viewing at the normal rate, this representing the actual analog-to-digital conversion of the data.

To understand the basics of a CCD, one must understand that a controlled spatial area can be neutralized of any charge. Then these areas can be gated to allow charging the potential of the preconditioned signal at the sample time. When that is achieved the gate is closed. We now have a "bucket" that is filled or charged to some level. So far it seems reasonable but now what happens to this level? Figure 7 is a very simplified diagram of the principle behind the CCDs used in the Tek 2430. Each of the squares represents a cell and each of these cells contains four gates (hence this is a 4-phase CCD). At the sample pulse rate two gates are used as control devices with two holding the charges. Figure 8 shows an example.

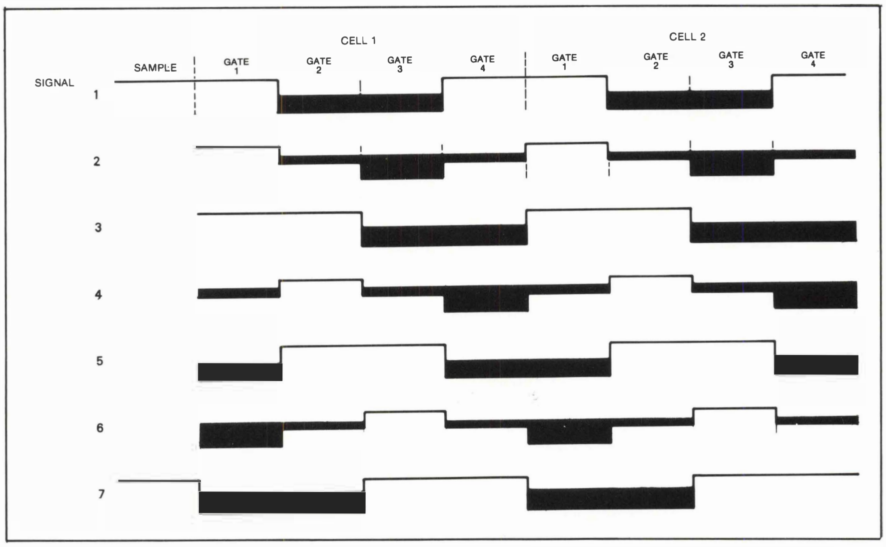


Figure 8. This figure represents the way in which a charge is transferred from gate to gate in each cell and thus from cell to cell. Gate 1 and 2 are clocked at an approximate 4ns phase difference while Gates 3 and 4 are 180 degrees out of phase with 1 and 2 respectively. In the first example, Gate 1 is high and 2 and 3 are low or on, the charge being shown in Gates 2 and 3, while 4 is high. In Example 2, Gate 1 is still high; Gate 2 has started to go high, while Gate 4 is going low. The charge starts to flow from Gate 2 through Gate 3, which is still low, and then into Gate 4 which is changing state. The third example shows Gates 3 and 4 charged; thus the charge has been transferred from 2 and 3 to 3 and 4. This process is continuous with each sample pulse.

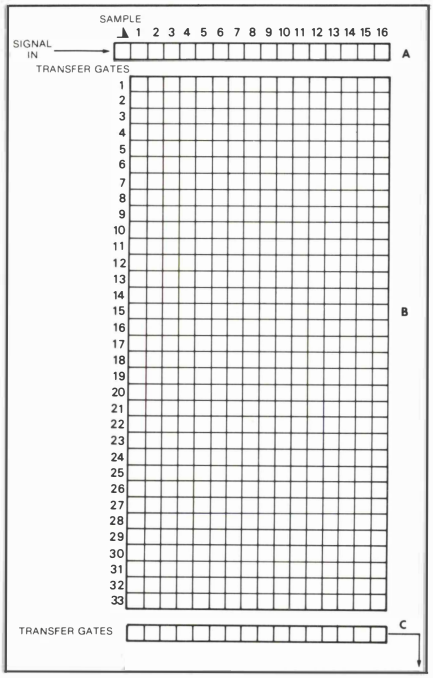


Figure 7. This drawing represents one half of the input, memory and output cells available in the Tek 2430 CCD. Section A represents the serial input cells, B represents the memory section, and C represents the output cells.

The number of cells in B represents the number of data points that the device can hold in any one acquisition cycle. This is essentially the memory capability of the CCD. In the 2430 the data record is 1024 samples. For simplicity, Figure 7 represents only half the memory available in the 2430. If your math is correct you will find that there is actually 16 x 33 cells or 528 x 2 = 1056 samples available in the CCD. The extra 32 bits is used to keep track of trigger points, etc.

The acquisition of the data is achieved similarly to a shift register. In transfer Gate A on the diagram, the sample pulse turns on the first gate, and a charge is accumulated in Cell 1. The CCD is gated such that the charge is transferred to Cell 2, then the sample pulse allows cell 1 to charge again. We continue this charge couple effect until the 16 cells in the transfer gates are filled. At that time those cells are transferred. This process continues until we get to the transfer out gates, C on the diagram.

From this point the data is transferred serially to the analog to digital converter; in the case of the 2430, a fast successive approximation converter is used. Here the data is quantized and stored in memory, displayed on the CRT, then processed or manipulated in some manner. The CCD offers the capability of increasing the sample rate without excessive cost. In the case of the 2430, we have a sample rate of 100MHz, a record length of 1K per channel and 8-bit vertical resolution at a very modest price when compared to instruments of the same performance level.

Scan Conversion

This method is used in Tek's signal processing systems instrumentation. It involves storing the information on a target in the CRT and reading off this data using a separate scanning beam on the other side of the target. Very high effective bandwidths, as in the Tek 7912 500MHz sample rate, can be achieved using this technique. It is, however, quite expensive and dependent on the writing beam's intensity, similar to conventional CRT storage. The digitizer is also unavailable for input while the written trace is being scanned. See Figure 9.

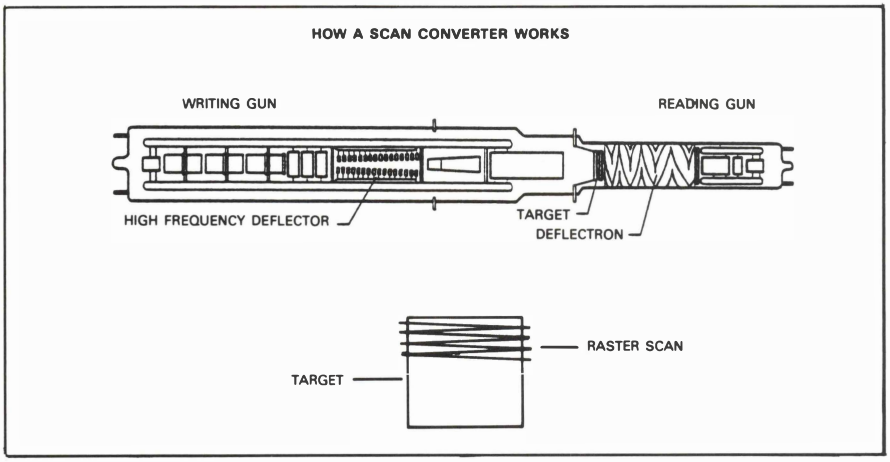


Figure 9. A scan converter contains a double ended CRT. The writing beam is like that in an oscilloscope CRT, except that it uses a very small and very special target, a silicon diode array. The target is then read by a slower reading beam that scans across it in a raster similar to that used to build up a picture on your television screen.

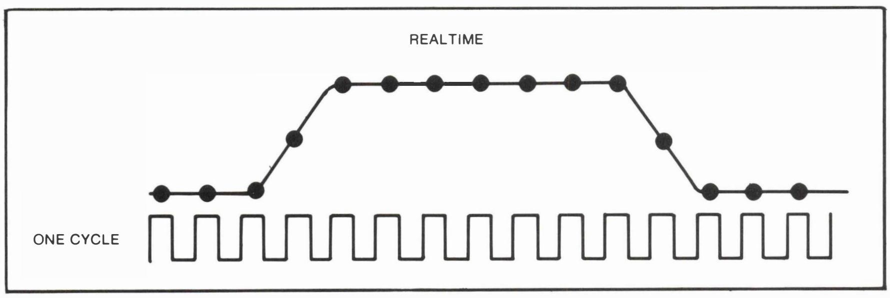


Figure 10. A waveform is sampled in a single pass. The sample rate must be high enough to acquire sufficient data points to reconstruct the waveform.

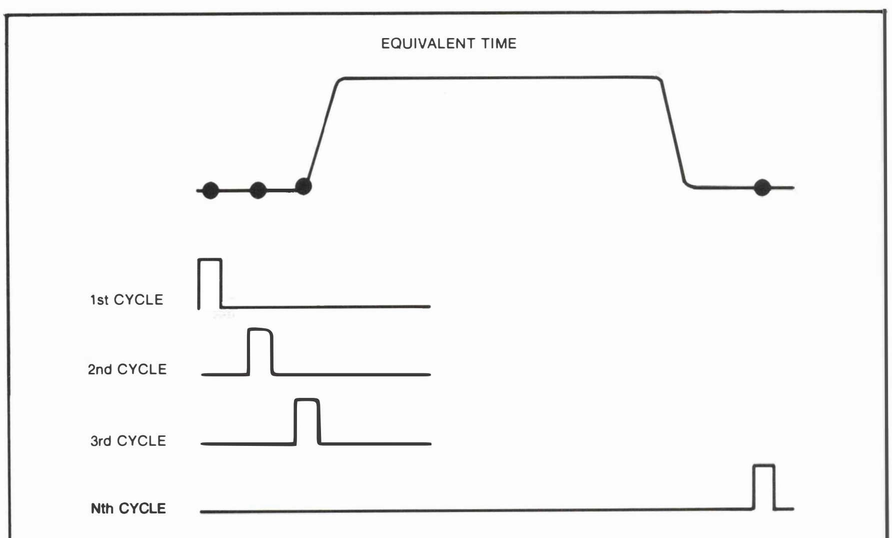


Figure 11. Sequential sampling samples one point on the waveform for every acquisition cycle. This is done sequentially and is repeated until enough points are acquired to fill the memory. If memory is one thousand points long, it would take one thousand passes to acquire the waveform.

SAMPLING TECHNIQUES

There are two digitizing techniques that should not be confused: real-time sampling (all samples for a signal are acquired in a single acquisition) and equivalent-time sampling (the signal must be repetitive as the stored signal is built up by sampling many waveforms). Digital storage scopes use real-time sampling so that they can capture both repetitive and single-shot signals. Figure 10 shows an example of real-time sampling.

Sampling scopes use equivalent-time sampling and are limited to capturing repetitive signals. Some digital storage scopes use equivalent-time digitizing to extend their useful frequency range. The Tek 2220, 2230 and 2430 use this method.

The two equivalent-time techniques—random sampling and sequential sampling—build up a picture of the input waveform by capturing a little bit of information from each signal repetition. Eventually they have enough information to reconstruct the entire waveform. Figures 11 and 12 are examples of these two types of waveform acquisition.

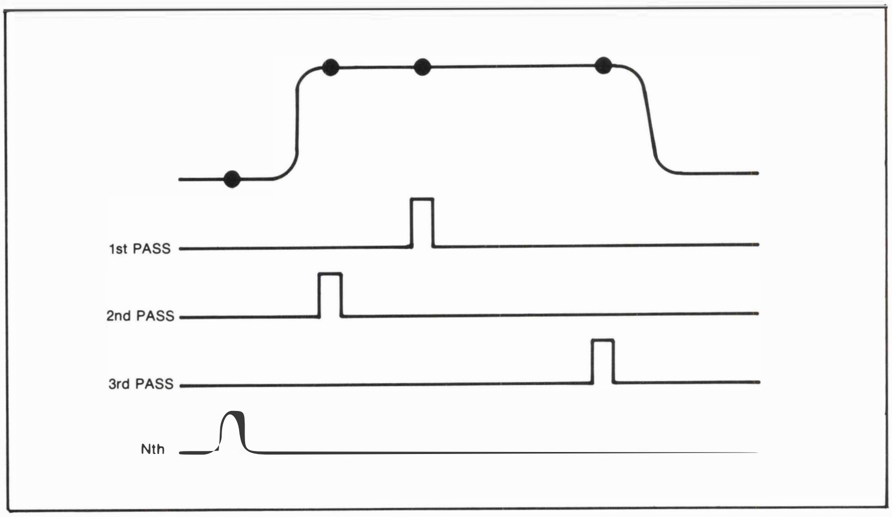


Figure 12. Random sampling acquires signals at a random sequence in relation to where they are stored in memory. The points in time at which these samples are acquired are "remembered" in reference to the trigger point. This type of equivalent-time sampling has two advantages. First, since the points are reconstructed in reference to the trigger point, we retain pre- and post-triggering capability, which sequential sampling cannot do. Second, because we are referenced to the trigger signal the normal digital trigger jitter is not a factor.

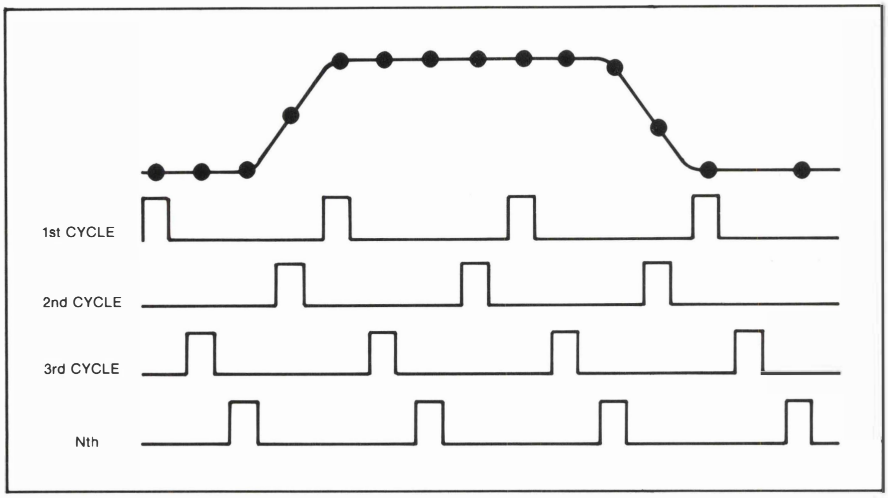


Figure 13. Multiple point random sampling acquires several points in one acquisition cycle, thus reducing the acquisition time considerably. As an example, the 2230 acquires a minimum of 10 points per cycle, so it would improve the acquisition time by at least an order of magnitude over a scope that acquires a single point on each cycle.

Not all signals you need to store are repetitive. Some happen only once; some happen so infrequently that they might as well only happen once. This last category includes pulses that occur less than once in a second. If a scope memory is 1024 words long, it would take over 1000 seconds, or over 15 minutes, for a sampling scope to build a picture at that rep rate. There is, however, a method of reducing this acquisition time, incorporated in the 2220, 2230 and 2430. We call this technique multiple point random sampling. An example is shown in Figure 13.

If you work with repetitive signals, equivalent-time sampling can also extend the bandwidth of your scope. A sampling plug-in like the 7S12 for Tek 7000 Series scopes enables you to store signals to 14GHz.

Envelope or Peak Detection Methods

The 2230 uses a digital method of peak detection. In this mode the signal is always sampled at the maximum possible sample rate. This method is limited by the digitizer's sample rate. In the 2230, the sample rate in this mode is 10MS/sec. You can, therefore, be assured of capturing a half amplitude 100 ns pulse at any sweep speed. The scope also offers some capability in processing these captured minimum and maximum values, to be discussed in the processing section.

Another method of peak detection is called analog peak detection, as used in the Tek 2430. With analog peak detect you are no longer limited to the digital sample rate. You are now limited only by the analog peak detect or "sample and hold" circuitry. In the case of the 2430, you have the ability to detect signals as narrow as 2ns at any sweep speed. More will be mentioned about peak detection when we discuss aliasing.

OTHER DIGITAL SCOPE CHARACTERISTICS

Horizontal Jitter

One of the characteristics of older digital storage scopes is horizontal jitter that occurs with multiple acquisitions of a signal. The jitter is ± ½ a sample interval (a sample interval is the amount of time between samples) and is a result of the way digital scopes store the waveform. A digital scope is always acquiring the input signal; it doesn't wait for the trigger event like an analog scope. Consequently, there is no consistent timing relationship between the digitizing clock and the trigger event. So on successive triggers and repaintings of the signal, the relationship between the clock and the waveform on the screen can vary ± ½ a sample interval. The trace then appears to jiggle back and forth on the screen as in Figure 14, and this severely limits the usefulness of the instrument in magnified viewing.

Horizontal jitter does not appear with single acquisitions, and with the newer Tek DSOs—the 2220, 2230 and 2430—jitter is unobservable even during horizontal expansion of repetitive signals.

Digitizing Rates

Sampling rate or digitizing rate specifications are expressed in a number of ways. Most common is frequency (20Mega samples per second or 20MS/s). The next most familiar would be (20MHz sample rate) or number of samples/second. Sometimes the information rate is given; this is the number of bits of data stored in a second (160 million bits a second). To translate an information rate into frequency, just divide by the number of bits the ADC uses (in this case, assuming an 8-bit A/D, 160M bits/8 = 20Mega samples per second). Sample interval or a time/point is also used (50ns per point); this is the reciprocal of the frequency.

To determine the digitizing rate for a particular TIME/DIV. switch setting:

$$\text{Digitizing Rate} = \frac{\text{Number of Data Words/Div.}}{\text{Time/Div.}}$$

The number of data words per division is:

$$\text{Number of Data Words/Div.} = \frac{\text{Record Length of Waveform}}{\text{Sweep Length in Divisions}}$$

For example, if a waveform is stored in 1024 data words and the scope shows all 1024 points within 10.24 divisions, as does the Tek 2230 (some scopes use a screen size of 10 divisions), then the number of data words per division is 100. Dividing that by the TIME/DIV. setting gives you the digitizing frequency. For 1 second, it would be 100 Hz; for 10 microseconds, it is 10 MHz.

DISPLAY TECHNIQUES

You may want to view a waveform once it has been digitized, memorized and processed, and you have not shipped results to a computer. There are several methods that may be used to redisplay the waveform.

Basically, you can use dots, vectors joining the dots (sometimes called linear interpolation), sine interpolation and a modified sine interpolation. But first we need to discuss how digital data can be displayed as a waveform.

Digital to Analog Converters (DAC)

All methods require a digital to analog converter to change the data back to a form the human eye can understand. Digital-to-analog converters (DAC), when used for reconstructing the digital data, do not require the performance characteristics that A to Ds need since the conversion rate is so much slower. The DAC's main purpose is to take the quantized data and convert it to an analog voltage. Most DACs use a parallel input circuit; this design accepts a parallel binary input code. If you need to convert the information from an 8-bit analog to digital converter (or the processed data) back to an analog voltage, then you would need at least an 8-bit input D to A.

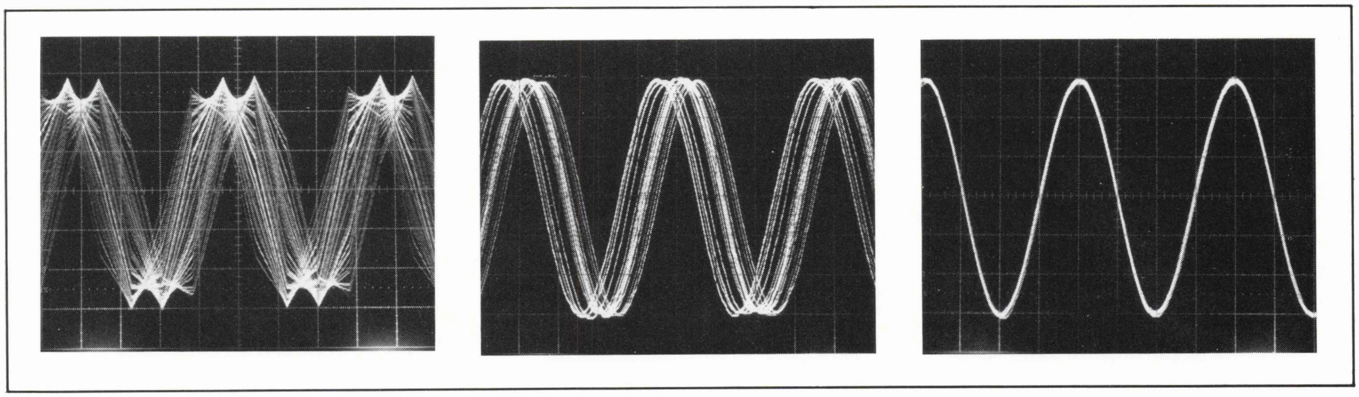


Figure 14. The waveforms acquired by a digital scope are digitized under the control of a free running clock. When multiple acquisitions of a signal are stored, the timing relationship between the clock and the trigger can vary ± ½ sample interval. Horizontal jitter is the result. Jitter is minimized by using large memories to store the waveform (which makes each horizontal element smaller), but the jitter will still limit horizontal magnification. Jitter correction is a feature of some digital storage scopes. Actually, any DSO that has random equivalent time capabilities has this feature built-in, as it is necessary to know where the sample points were sampled in relation to the trigger point. This is the case in the 2230 and 2430. With these instruments, there is little jitter in either normal or magnified viewing. The photos above are the result of many acquisitions of a 5MHz sine wave. The first display may be familiar to users of digital scopes. The second shows the effects of sine interpolation and the third shows the effect of a jitter correction circuit.

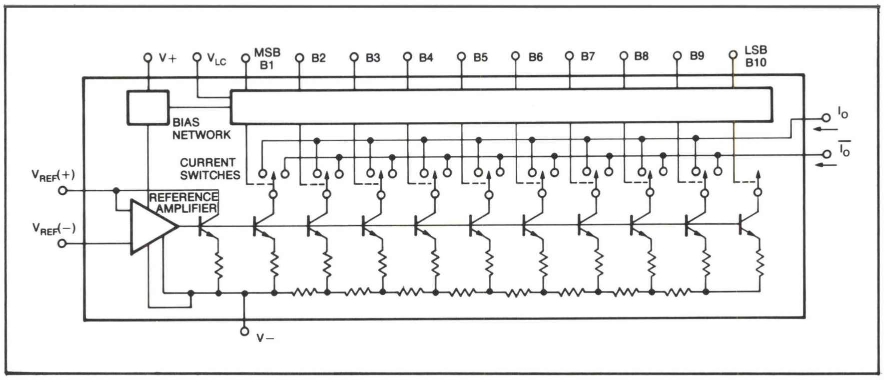


Figure 15. In this case, even though the ADC is an 8-bit device, the DAC is a 10-bit device in order to take advantage of the average mode to display 10 bits of vertical resolution. As you can see, which bits are high determines where the transistor's current will flow. Different words will cause various levels of current to be available, which can be converted to voltage levels for each word.

This input code is converted to an analog voltage by using binary weighted switches that react simultaneously to the binary input data. Figure 15 shows an example of the DACs used in the 2230 and 2220.

A discussion of displaying the reconstructed waveforms should also mention a limitation that may occur, called aliasing.

Aliasing

The first of two types is called perceptual aliasing. Perceptual aliasing is inherent in dot displays and is essentially a kind of optical illusion.

Actual aliasing occurs when a signal is sampled less often than it should be; as a result the signal might be taken for an "alias" signal of a much lower frequency. See Figure 16.

The danger in aliasing lies in the fact that you might not even know it is occurring. You can be reading the signal with your scope and completely miscalculate what the real input was.

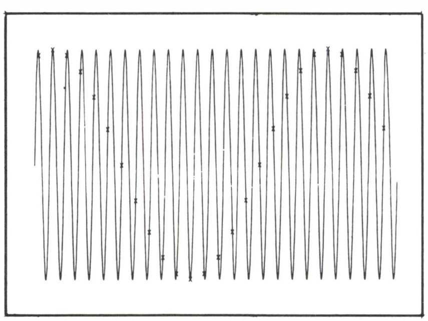


Figure 16. Sampling theory states that a periodic signal must be sampled at more than twice the highest frequency component of the signal. Otherwise, aliasing will occur. The figure above demonstrates undersampling. Here the signal is sampled only once a cycle, where the ratio of sample frequency to input frequency is 1.1. The alias waveform is of a much lower frequency: 1/19 the actual input frequency.

Obviously, more samples per period will eliminate aliasing. But trial and error selection of sample rate or sweep rate, will most likely result in error. To be certain, a quick calculation can be made to determine the minimum sweep rate.

For those scopes in which the user selects time scale by a TIME/POINT control, it is very straightforward to select the sample rate. More common, however, is having a TIME/DIV. control by which the scope computes the necessary sample rate to fill the screen. In the newer Tek scopes and in most general purpose applications, there are more than enough points displayed for viewing the waveform. The sample rate depends on the memory length of the waveform display, the number of horizontal divisions, and the sweep speed, as shown in the formula below:

$$SR = \frac{\text{(Time/Div.) x (Number of Horizontal Div.s)}}{\text{(Displayed Record Length)}}$$

Example:

given, Time/Div. = 50 microseconds/div.
Record length = 1024 points/wfm
Number of divs = 10.24 divs/wfm

$$SR = \frac{50\ \text{(ms/div.)}\ 10.24\ \text{(divs/wfm)}}{1024\ \text{(points/wfm)}} = .5\ \text{ms/point}$$

and the sample frequency is simply,

$$fr = \frac{1}{SR}$$
$$= 2.0\ \text{MHz}$$

This, of course, is useful only if it can be related to the actual measurement. In many cases, the needed bandwidth can be estimated for a given application. So, by determining the scope's maximum sampling frequency, the bandwidth limitation can be determined.

We know that we must always digitize twice as fast as the highest frequency in the signal. The simplest way to do so is to make sure you pick a TIME/DIV. setting that results in a high enough digitizing rate. If you cannot do that, you can use an anti-aliasing filter to eliminate frequencies above the Nyquist limit (see glossary). This avoids aliasing, but it also removes any indication that higher frequencies are present in your signal. (Note that a bandwidth limiting switch is not an anti-aliasing filter. The rolloff of a bandwidth limiting device is usually 6 dB/octave; however, unless an anti-aliasing filter has at least 12 dB/octave, some high frequency components will still appear as aliasing.)

Dot Displays

Dot displays are, just as their name implies, made up of points on the CRT. They are useful as long as you have a sufficient number of points to reconstruct the waveform. The number of points required is generally considered to be on the order of 20 to 25 points per cycle, as discussed in the Useful Storage Bandwidth Section.

One consideration in dot display mode is this: as the frequency of your input signal increases with respect to the digitizing rate, fewer dots will be available to form the trace. This results in perceptual aliasing errors, especially with periodic waveforms such as sine waves. Perceptual aliasing, as discussed earlier, is a kind of optical illusion (Figure 17) that occurs because your mind tends to form continuous waveforms by connecting each dot with its nearest neighbors when viewing a dot display. The next closest dot in space, however, may not be the next closest sample of the waveform. The result: you can easily misinterpret the data on the screen. It takes a large number of dots (about 20 to 25 for every cycle of the sine wave) to present a recognizable display.

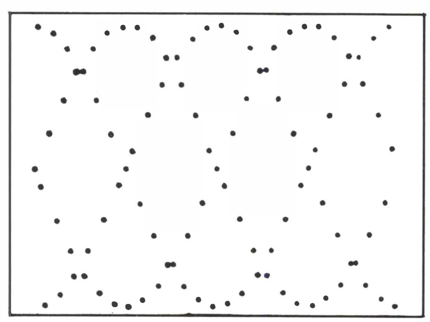


Figure 17. Perceptual aliasing errors are so named because sometimes the dot display can be interpreted as showing a signal of lower frequency than the input signal. But this is not true aliasing. The actual waveform is there; your eye—not the scope—makes the mistake. Note that in the drawing what seems to be many untriggered sine waves is really one waveform.

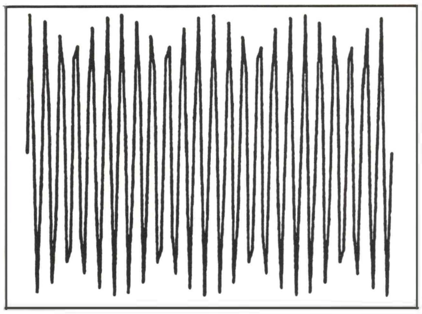


Figure 18. When vectors are drawn between the points in Figure 17, note that vector displays can prevent perceptual distortion but can still show peak amplitude errors when the data points do not fall on the signal peaks.

Pulse Interpolation or Vector Display

Perceptual aliasing is easily corrected by adding vectors to the display as shown in Figure 18. But the envelope error can still persist because the vectors are only straight lines joining the data points. The signal could still lie outside the waveform traced by the vectors.

Some digital storage scopes use a vector generator which draws lines between the data points on the screen. When this interpolation is used to display a sine wave, perceptual aliasing is eliminated and only 10 vectors per cycle of the sine wave are necessary to reconstruct a recognizable display. Pulse interpolators also make glitches more visible by connecting every data point and preventing a single dot far from the rest of the waveform from being overlooked.

As long as the vectors on the screen are short, an accurate representation of the input sine wave is possible. But with long vectors, the displayed waveform and the input signal may not coincide. A linear interpolator can indicate a different shape for the waveform anytime the samples taken by the scope do not fall exactly on the peaks of the signal.

Sine Interpolation

Another display reconstruction technique uses an interpolator designed for reproducing sine waves. As long as no aliasing took place when the original data words were gathered, this interpolator will not introduce errors when displaying sinewaves. The sine interpolator in the Tek 468 illustrates the advantages of this display type for reconstructing sinewaves; only 2.5 data words per cycle are necessary to display the signal as shown in Figure 18a.

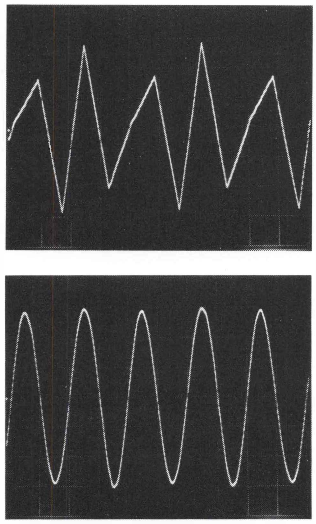


Figure 18A. The above photos show a 10MHz waveform, sampled at a 25MHz sample rate, displayed in a linear interpolated format and a sine interpolated format. For sine waves, sine interpolation helps to extend the useful storage bandwidth of the digital storage oscilloscope.

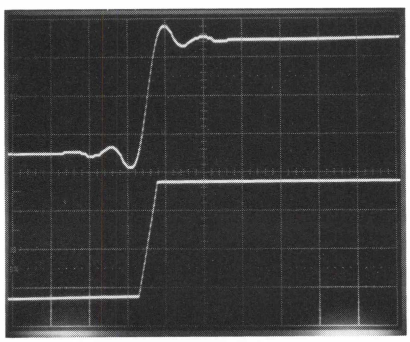


Figure 19. Displays constructed with sine interpolation avoid perceptual aliasing and envelope errors when used to display sine waves. But an interpolator designed for good sine wave response can add what appears as pre- and over-shooting to the display of a step function when there are less than three samples taken on the step. The error is minimized if more than three samples are taken and with narrow spectrum waveforms such as sine waves. The photo above is a double exposure of a signal with no samples on the step; the first trace is drawn with a sine interpolator and the second with a pulse interpolator.

The same interpolator that makes sine waves more accurate introduces what appears as pre-shooting and over-shooting on pulses (see Figure 19).

Modified Sine Interpolation

As mentioned above, one of the drawbacks of sine interpolation is the introduction of aberrations on a pulse. One method of alleviating this is to use a digital pre-filter. The digital filter coupled with the sine interpolator permits reconstructing the waveform to a better representation of the actual waveform. Figure 20 shows the principle behind the pre-filter used in the 2430, while Figure 21 shows an actual pulse on the 2430 in equivalent time and with the filter off and with the filter on.

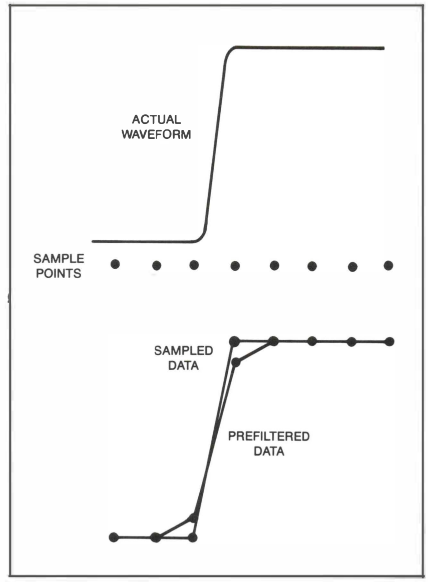


Figure 20. The pre-filter looks at the slope of three samples, then the next three, and then checks for a discontinuity between the slopes. If there is a discontinuity of more than one division between the compared slopes, the closest points to the discontinuity are adjusted by about 10% of the amplitude, as shown by the blue line. This waveform is then processed by the sine interpolator and, since the risetime has been effectively "rolled off," the pulse is reconstructed without the normal "ringing" associated with sine interpolation.

Envelope or Peak Detect Mode

Envelope mode is a method of sampling used to detect aliasing, first implemented and patented on the Tek 468.

When in this mode, the digitizer is always sampling at the fastest possible digitizing rate for the instrument. Vectors are then drawn between the highest and lowest values. The result is a display that looks much like a conventional scope. See Figure 22.

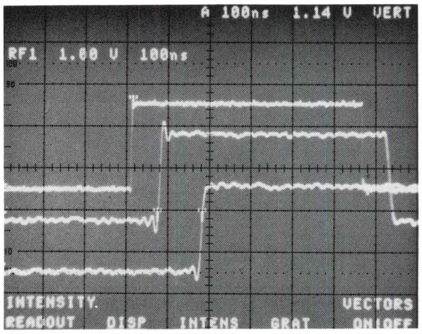


Figure 21. The top pulse in the photo is a pulse acquired in equivalent time mode, which represents the actual waveform. The middle pulse is of the same pulse acquired in the sine interpolate mode with the pre filter off; the same pulse is shown below on the 2430 DSO, acquired with the filter on. The sine interpolator introduces ringing on the leading edge of the pulse, and the filter helps to make the display more representative of the waveform.

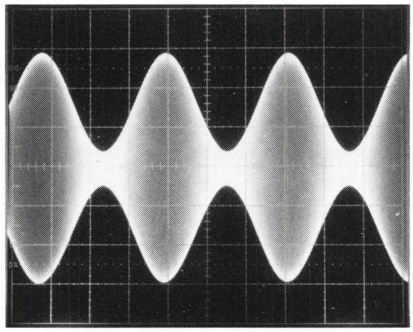
In the normal operating mode of a digital storage scope, the input signal is digitized at the frequency related to your TIME/DIV. switch setting. One data word is stored in memory for every sample taken. In the envelope mode of the 2230, samples are taken at a much faster rate but recorded at the frequency specified by the TIME/DIV. switch. Instead of recording just one data word for each sample, however, two are recorded: the minimum and the maximum. The results of this kind of digitizing are shown in the drawings in Fig. 22A.

Roll Mode

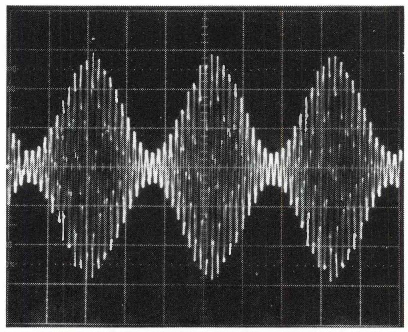
Another form of display may be described as an electronic chart recorder. This method, known as roll mode, is usually used on slower sweep speeds on the 2220, 2230 and 2430. This mode disables triggers; signal data is continuously acquired and displayed. The waveform display scrolls from right to left across the CRT with the latest samples appearing at the right edge of the CRT. See Figure 23.

Pre-Trigger

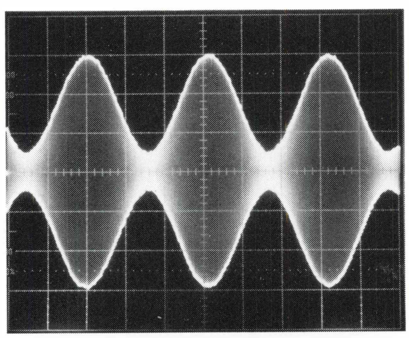
Another feature of digital storage that may be deemed a display technique is the ability to select a trigger point in time relation of the waveform. This pre-trigger capability allows you to view events that occur before the trigger, offering many user benefits.



NON-STORAGE



NORMAL MODE



ENVELOPE MODE

Figure 22. These photos are of an amplitude modulated signal as it was displayed by a non-storage scope, by a digital storage scope, and by a digital scope using the envelope mode. The modulating frequency is reproduced easily in both digital acquisitions. The carrier, however, is being digitized at a rate much less than two samples per period and is shown as a lower frequency in the middle photograph. The envelope mode used as an anti-aliasing feature results in a display very much like the non-storage signal. If the carrier had been at a lower frequency and digitized appropriately, the envelope and normal mode displays would have been similar.

The Tek 2230 can trigger on every 4 data points in a 4k record starting at 0 or every point in a 1k record. Figure 24 is an example.

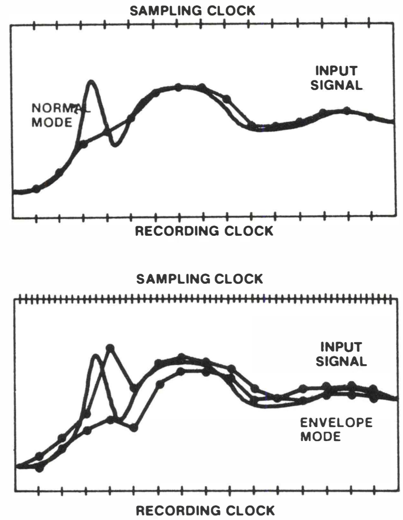


Figure 22A. As the illustrations show, a signal excursion that occurred between the normal sampling points is captured and displayed by the envelope mode. The envelope mode has an obvious use in detecting aliasing, but it also has other uses, as will be discussed in greater detail later.

ROLL MODE

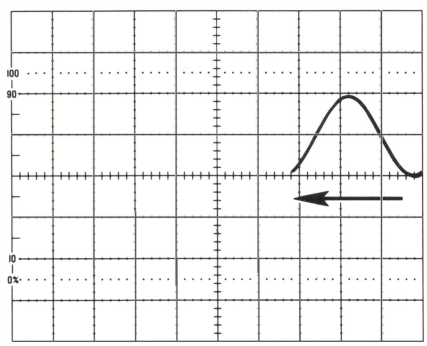


Figure 23. An extension of this feature, "Scan Roll Scan" is implemented on the 2230. It is useful if you need to look for an event that occurred randomly on a level waveform such as a DC power supply.

The scope will continuously scroll from the selected trigger point until a trigger is detected, at which time the rest of the waveform will fill after the trigger point and be saved in memory.

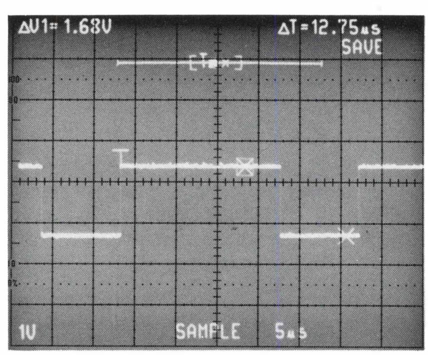


Figure 24. The 2230 has a trigger point indicator located both on the waveform and the "memory bar indicator" as shown in the above photograph. The trigger point is indicated by a "T" on the display.

USEFUL STORAGE BANDWIDTH AND USEFUL STORAGE RISETIME

Now that we know some of the methods of displaying digital information, let's look at how we can best use the different methods.

One of the primary reasons for using storage is to display events that happen only one time, i.e., single-shot events. In CRT storage, this is usually specified as single-shot bandwidth and there is a well defined method of checking it. With digital storage it's not quite as easy. Your particular application and the capability of the DSO may be different than another user's so we will explain several possible methods. We will call this "useful storage BW" or, in the case of rise time, "useful storage rise time."

Useful Storage Bandwidth

Bandwidth is the specification that describes the ability of a scope to display sine waves. When you add a camera to a non-storage scope to make it a storage instrument, however, you use another specification as a criterion: photographic writing speed. With direct view CRT storage scopes, the stored writing speed specification is usually your criterion for choosing the instrument. Why use writing speeds rather than bandwidth? Because usually it is the amount of charge (or light) that can be deposited on the target (or film) that forms the upper limit of the instrument's storage capabilities; it is not usually the frequency response of the instrument's amplifiers. Of course, both writing speeds are directly related to the frequency of the signal that these instruments can store; see Figure 25.

When it comes to digital storage scopes, most users prefer a single figure of merit—like bandwidth or writing speed—that describes the maximum signal frequency these instruments can store. Useful storage bandwidth is a way to specify that maximum "useful" frequency.

We have previously described how the digitizing rate of a digital scope changes with the sweep speed you select. The same chapter described

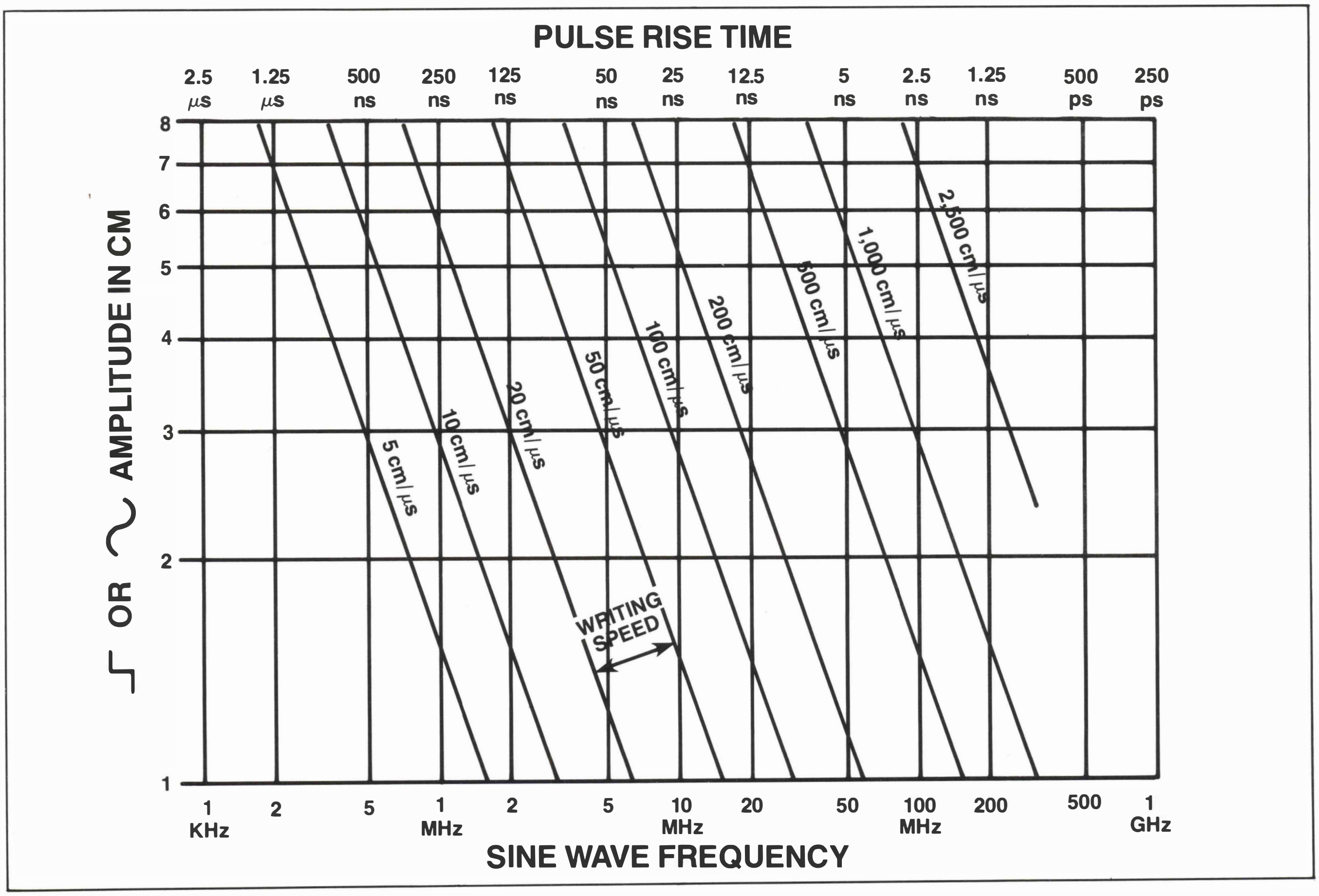


Figure 25. How quickly a CRT storage scope must write on the screen is dependent on the speed of the input signal and the amplitude of the signal that you want to view on screen. The chart above shows amplitude in centimeters vertically and the speed of the input signal along the horizontal axis. For sine waves, use frequency; and for pulses, use rise time to determine the writing speed necessary to store the signal.

the influence of display reconstruction on how easily you can identify and measure sine waves on a digital scope. Both factors enter into the useful storage bandwidth; it is dependent on digitizing rate and on display type as Figure 26 illustrates.

Dot displays suffer from perceptual aliasing and from envelope errors. To reduce or eliminate these, at least 20 and preferably 25 samples of each cycle in a sine wave must be displayed. So for a full scale, sinusoidal signal, the useful storage bandwidth (USB) is defined as:

$$\text{USB(MHz)} = \frac{\text{Maximum Digitizing Rate(MHz)}}{25}$$

Note that the number of samples/cycle necessary to recognize the input signal on a dot display changes with the amplitude of the

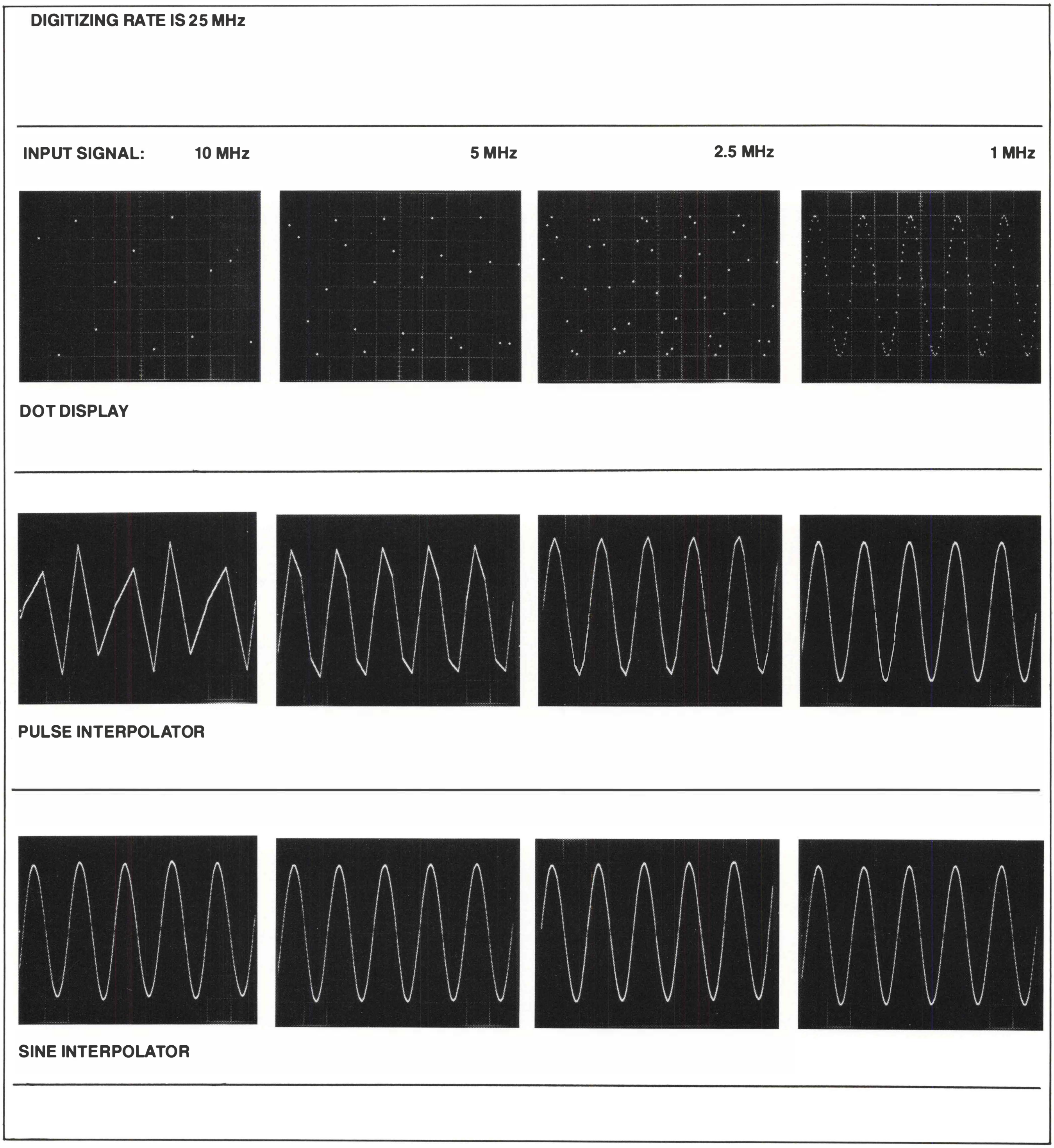


Figure 26. The display reconstruction type influences the useful storage bandwidth of a digital scope. To trace a recognizable sine wave takes at least 20 and preferably 25 samples per cycle with dot displays. Pulse-interpolator displays produce a useful trace with about 10 vectors per cycle; peak errors make your measurements more difficult when fewer are used. The sine interpolator in the Tek 2430 display shown in the lower series of photographs reproduces sine waves with only 2.5 samples/cycle, finally approaching the limits that the sampling theory suggests.

trace. If the trace is smaller, then the data points on the screen are closer together and perceptual aliasing is reduced.

In this respect, the useful storage bandwidth for dot displays is similar to a writing speed specification. This is not true for either of the interpolated displays.

Interpolation is another subject introduced previously; it is the addition of data words between the original sampled points. When a linear interpolator is used and vectors are then drawn between all the data points, recognizing a sine wave is much easier, though envelope errors still remain. For a linear interpolator, then, the useful storage bandwidth is defined as:

$$\text{USB(MHz)} = \frac{\text{Maximum Digitizing Rate(MHz)}}{10}$$

A sine interpolator results in a further improvement in your ability to perceive and measure sine waves. For the sine interpolator used in the Tek 2430, the useful storage bandwidth is:

$$\text{USB(MHz)} = \frac{\text{Maximum Digitizing Rate(MHz)}}{2.5}$$

Please note that the useful storage bandwidth divisor above is dependent on the particular interpolator used in the instrument; not every sine interpolator is the same.

Useful storage bandwidth can be used for more than comparing digital storage scopes to digital storage scopes; it can also be used to compare the performances of analog and digital scopes. Compare the useful storage bandwidth to bandwidth directly, or derive a useful storage bandwidth from a writing speed specification with:

$$\text{USB(MHz)} = \frac{\text{Writing Speed(DIV./ms)}}{10}$$

That corresponds to a fully written sine wave 3.2 divisions in amplitude; writing speed units are in screen divisions per microsecond and not centimeters since screen sizes vary and because your measurements are made in terms of divisions. The formula is somewhat arbitrary, but it will give you a figure you can use for comparison purposes.

Useful Rise Time

Not every measurement involves sine waves. The parameter that reflects a storage instrument's ability to accurately record pulses is rise time. For analog instruments, the rise time may be approximated from the bandwidth:

$$T_r(\text{ns}) = \frac{.35}{\text{BW(MHz)}}$$

When you try to measure an input signal's rise time that is much faster than the rise time of an analog scope, what you actually get is the rise time of the system: scope and input combined.

The measured rise time in this case is approximated by:

$$T_r(\text{measurement}) = \sqrt{T_r(\text{signal})^2 + T_r(\text{instrument})^2}.$$

For digital scopes, however, simple geometry shows that if a very fast signal is measured and displayed with a pulse interpolator, the displayed rise time can vary from 0.8 to 1.6 sample intervals. As Figure 27 shows, the displayed rise time depends entirely on where the samples fell on the input signal.

It turns out that the maximum positive rise time errors produced by a pulse interpolated display closely follow the form of an analog scope's errors (Figure 28) when the analog system has a rise time of 1.6 sample intervals; maximum negative rise time errors are much smaller. Thus, because the most limiting measurement errors that occur when you use 1.6 sample intervals as the nominal

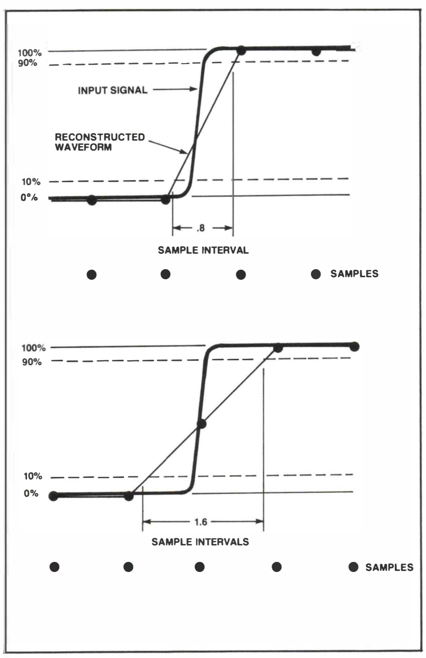


Figure 27. To demonstrate how the errors in a rise time measurement made by a digital system can change with the sample placements, the same input step is shown in both drawings. In the first, the step occurs exactly halfway between samples. The rise time of the resulting vector display (in blue) is 0.8 sample intervals in this situation. On a different acquisition of the same signal, however, the samples may fall as shown in the second drawing. In this worst case, the rise time indicated by the display is 1.6 sample intervals—the maximum possible.

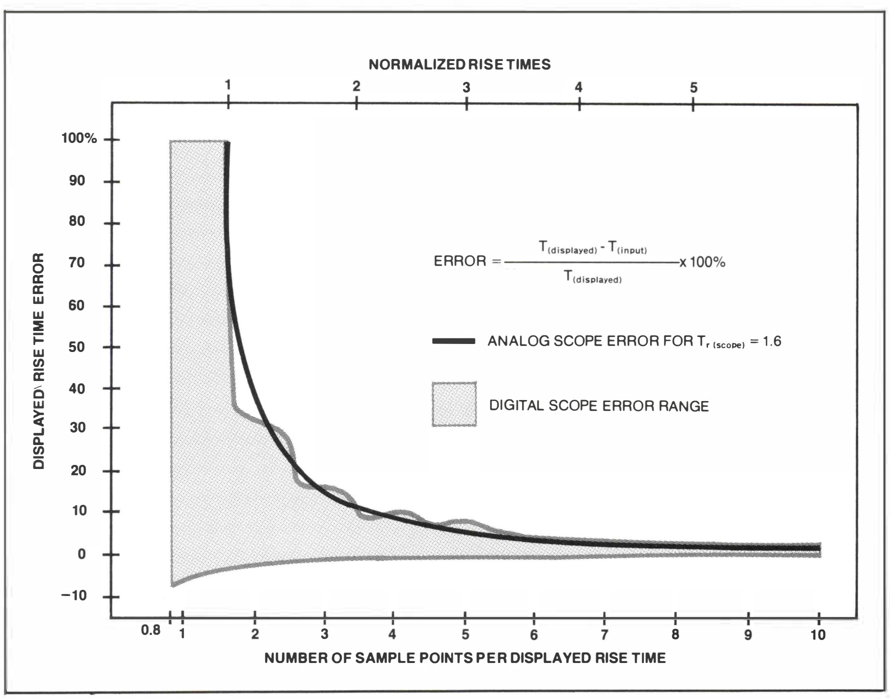


Figure 28. A computer model of a digital storage scope display was used to generate the rise time error ranges shown above. To make the results independent of any particular digitizing rate, the horizontal axis is the number of sample points per displayed rise time of the input step function, while the errors plotted vertically are shown in percentages of displayed rise time. The input step was a worse case—an exponential step. For comparison, the error curve of an analog system with an equivalent rise time is also plotted.

rise time are similar to the errors of an analog scope, the useful rise time can be defined as:

UTr = Minimum Sample Interval x 1.6

If, for example, you wanted the useful rise time of a digital scope with a maximum digitizing rate of 10 MHz, you would multiply the minimum sample interval (0.1 ms) by 1.6; the useful rise time is then 0.16 ms or 160 micro-seconds.

Note that the useful rise time is based on a pulse interpolator. Dot displays have additional error possibilities because of the truncation of resolution; with the same number of samples on the input step, the dots simply don't trace the shape of the signal. Interpolators designed for displaying sine waves show rise times that are faster than the input signal because of the pre-shooting and over-shooting introduced when there are only a few samples on the input step.

It is important to remember that—unlike the rise time of analog instruments—you cannot use useful rise time and the measured rise time to work back to the signal's rise time. The useful rise time is based on the worst possible error; the actual error in any given measurement can vary between the maximum negative and maximum positive values, depending on the placement of the samples on the input signal. The error range is graphed in Figure 28.

Note: Since your particular application may allow you to define your waveform in a number of points other than the above, these methods of defining useful storage bandwidths are only guide lines. One of the primary selection criteria must be the sample rate of the DSO since different manufacturers may define USB using different criteria.

The useful rise time and useful bandwidth parameters illustrate a significant difference between analog and digital scopes. While the analog instruments show a bandwidth and risetime that do not change with sweep speed, digital storage oscilloscope bandwidths and rise times change with the TIME/DIV. switch setting because of the changing digitizing rate. The useful bandwidth and useful rise time parameters, however, give you an indication of the fastest signals that can be captured with digital scopes, much as bandwidth and rise time specifications do for analog instruments.

SIGNAL PROCESSING

Signal processing is another possible feature offered by digital storage scopes. It includes translating of raw data into finished information.

Along with providing aliasing protection, enveloping or peak detection can also use the information for detecting glitches at sweep speeds much slower than possible in CRT storage. Because we know the timing relationship of the peak acquisitions compared to the time base sampling rate, and because we can display these minimum and maximum points by processing this information in relation to time and because we can draw them on the CRT, we have expanded the usefulness of peak detection to possibly an even more significant application, and that is glitch capture. See Figure 29.

With software/firmware, this function can be further expanded using a method sometimes called peak accumulate. Peak accumulate offers the ability to detect changes in a waveform over a period of time. By saving the mins and maxs over a period of time, the excursion of a waveform can be reconstructed with drift and jitter displayed. See Figure 30. Both the Tek 2230 and 2430 include this capability.

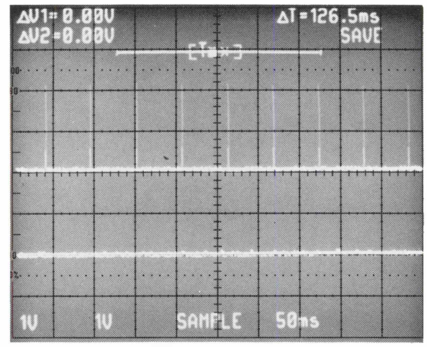
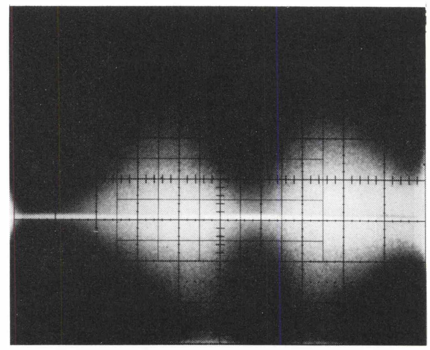


Figure 29. The top photo, top display, shows 100ns pulses at a sweep speed of 50ms on the Tek 2230. The lower display of the top photo shows that, without peak detect, pulses would not be visible. The lower photo shows the same sweep speed on a conventional CRT storage scope. Note that the pulse is not discernible on the conventional CRT scope.



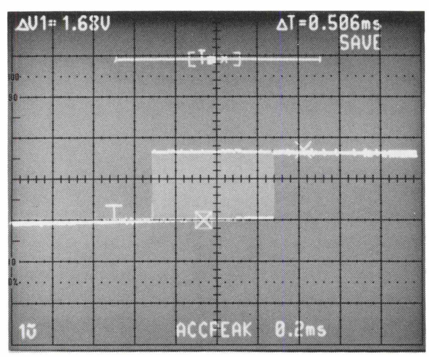


Figure 30. The signal has been drifting over a period of time. With the peak accumulate mode of the 2230 or 2430 you can detect and display the drift.

Save on Delta

Essentially, save on delta is accomplished by setting a predetermined envelope, then by positioning a waveform in the range of that delta. With the help of some processing, we would be able to save any waveform which went outside of the envelope; hence "save on delta." See Figure 31.

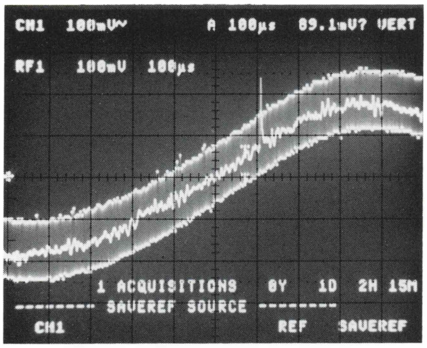


Figure 31. An envelope has been previously set up on the screen and in memory; the normal waveform was then positioned within the envelope. As long as the normal waveform remains in that envelope, nothing happens. As soon as there is an excursion outside of that envelope (as shown by the spike on the sine wave) the waveform is put into memory. An added feature in the 2430 is an elapse time clock that will tell you the time of the transient in relation to when you started the procedure.

Smoothing

The order in which mins and max points are displayed needs to be considered when using peak detect or envelope mode. Usually the points are displayed in an order of min-max, min-max as depicted in Figure 32, Display B. This gives you the ability to display "glitch" information but causes the displayed waveform to show jagged shapes in the magnified horizontal (this is usually not a problem when unmagged because the resolution isn't sufficient to see the jags).

Because of this the 2230 has incorporated, with patent pending, a logical and value reordering method called "smoothing." Data points are reordered for correct slope and interpreted for drawing smooth vectors. Smoothing looks at the change in value of data points between adjacent sample intervals. If the change in value does not exceed certain limits, the values are interpreted as a continuous slope for drawing vectors. If the value change exceeds the interpreted "no change" limit, the data point value is not modified, and the vectors drawn in the display show a discontinuity in the waveform. This method of display of the waveform data provides a smoothed display of the waveform, yet retains the glitch catching capabilities of the fast sampling that occurs during the time base period. Figure 32 shows results of the different methods.

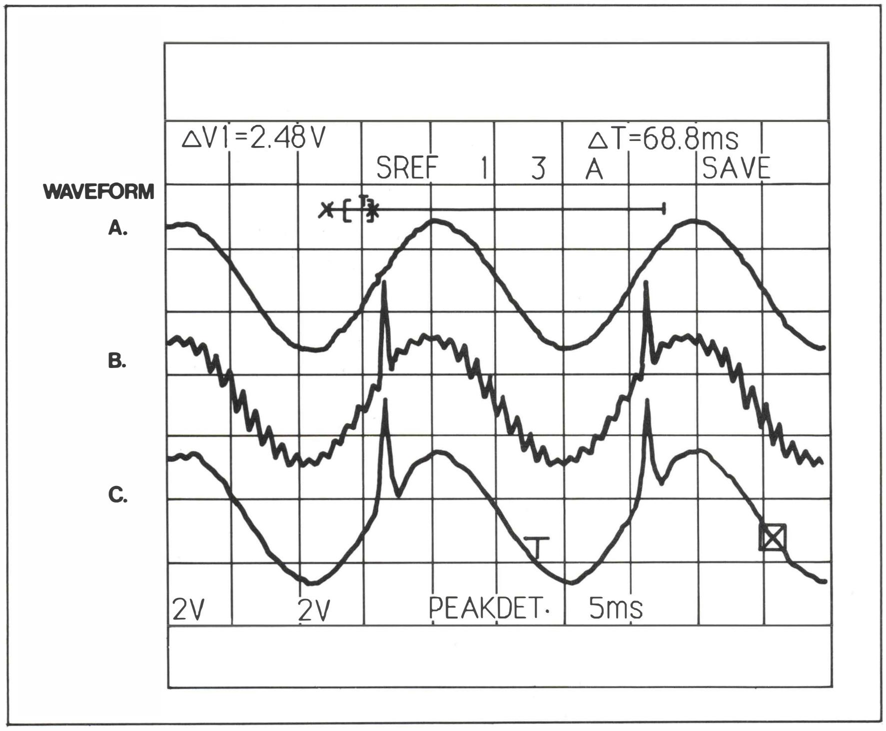


Figure 32. One problem with waveform reconstruction is pattern aliasing when using envelope or peak detect mode. This is shown in the X-Y plot waveform B. We need to use peak detect to ensure that there is no glitch in the waveform; but as in the waveform B, without smoothing we are not quite sure what the waveform is but we do see the glitch. In the C display, we see the glitch and a more representative waveform using smoothing. In the A display, using normal (sample) mode we have a representative waveform but miss the glitches.

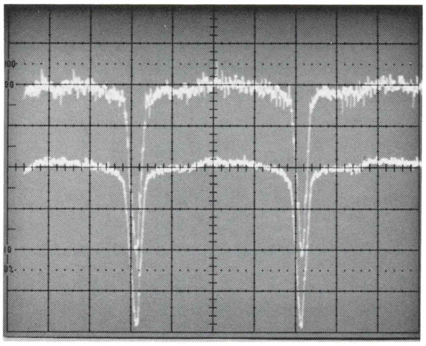


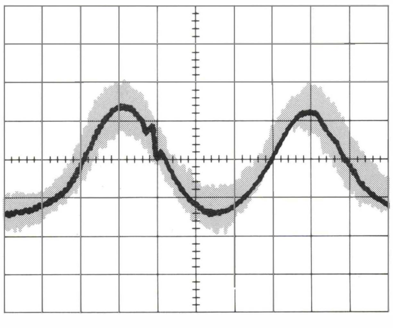
Figure 33. When a signal is digitized, the data that it represents can be manipulated in many ways. Some digital storage scopes use this opportunity for signal processing to increase measurement accuracy by averaging—or to reduce the noise component in the signal. In the photo above, a noisy display is saved, and the average of that same signal is displayed below, showing the increased resolution possible with signal averaging.

Averaging

Signal processing can also let you capture more accurate data—an example being signal averaging. This is a useful feature because, although sometimes it is the noise on a signal that you want to measure, most of the time it is not. Signal processing can eliminate noise by averaging many different frames of the signal as shown in Figure 33. Processing a signal with averaging can increase both the resolution and the accuracy of your measurements.

Increasing Resolution and Extending Accuracy with Averaging

The signal processing capabilities of a digital storage scope can increase the resolution of a signal so that the smallest unit can be distinguished. Suppose, for example, you need to make a vertical measurement on a noisy signal like the one represented by the drawing below.



The resolution of your measurement could be as poor as 1½ divisions and only as good as ½ division, depending on what part of the signal you were measuring. After averaging—represented by the line inside the noisy signal—your resolution would be closer to ⅕ or ⅒ of a division. Divisions are the units here because the voltage they represent depends on your VOLTS/DIV. setting.

With increased resolution, the accuracy of your measurements can also increase. The reason digital averaging has this effect is because the signal you want to measure is related to time in a very specific manner; it has the same trigger each time the scope reads it. The noise surrounding the signal, however, is not related to time and does not depend on a trigger. Because the noise is random, its arithmetic mean (average) is zero. As you average the waveforms, you increase the signal to noise ratio of the information you obtain. For uncorrelated noise, the S/N ratio is improved by a factor of the square root of "n," where "n" is the number of waveforms averaged. For example, if your measurements can vary by 10% because of noise, the signal to noise ratio is 10:1. Taking an average of four signals brings that up to 20:1 (10 times the square root of 4) or 5%.

There are several ways in which averaging can be accomplished. One method is by obtaining just a simple average:

$$\frac{\Sigma \text{ wfm data}}{n}$$

Where wfm = waveform n data
and n = number of averages.

Another method that can be used, as in the case of the Tek 2230 is by normalized averaging in which the last waveform acquired would have a weight assigned to it, i.e., 1, 2, 4, 8, 16...256.

The number of waveforms averaged is also selectable on the 2230. Any number from 1 to 2047, or no limit, can be selected. The algorithm for this average function is: $Avr_s = Avr_{s-1} + ((I_s - Avr_{s-1}) /2^n)$
Where:

- s = number of waveforms averaged
- Avr_s = average after s waveforms
- Avr_{s-1} = Previous average
- I_s = current waveform data
- n = positive integer ($0 <= n <= 8$), slaved to elapsed sweep

Figure 33A indicates the difference the weighting algorithm has on a series of randomly generated numbers.

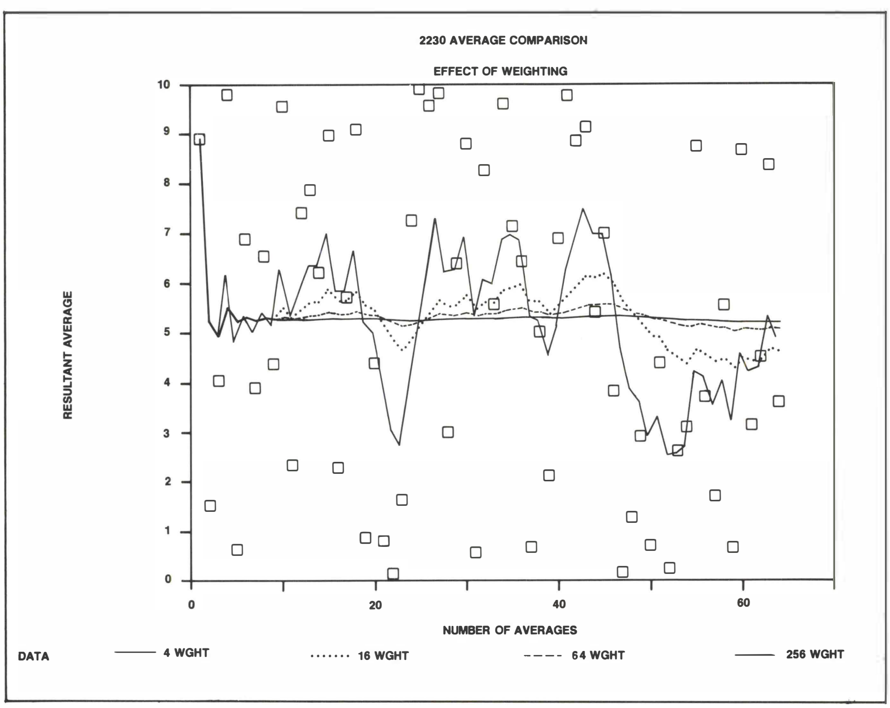


Figure 33A. The above graph is a computer generated set of random numbers that have been plotted and are represented by the small blocks. The blue line represents the improvement made by a weighting factor of 2^2, the dotted line is 2^4, the dashed line is 2^6, and the black line is 2^8. We can see that if we want to reduce the noise it is better to use the maximum weight, but if we are concerned about looking for changes in the signal then we would use a lower weight.

The above are certainly not the only signal processing capabilities that digital storage scopes offer. Two different signals can be digitally added, subtracted, multiplied or converted to an XY display by some instruments including the Tek 2430, 7D20 and 336. Some instruments will integrate or differentiate a waveform with the push of a button, as does the Tek 7854. In other words, signal processing can be of enormous benefit if your applications involve capturing waveforms and then finding out more about them.

Any number of math functions are also possible, including differentiation, DB RMS integration, etc. An instrument has the ability to send waveforms to external devices or computers, as do the 2220, 2230, 2430, 7D20, 336 and 7854. Digital storage offers another important advantage. You can still do the computation in a computer, even though the DSO doesn't have the computation ability built in. Data transfer will be discussed more later.

SPECIFICATIONS

Timing Measurements

The accuracy of the timing measurements you make with any scope is influenced by errors within the measuring system and limited by the system's resolution. For analog scopes, the sources of errors are the instrument's bandwidth and inaccuracies within the time base; the limit to resolution is the trace width. For digital scopes without interpolation of any kind, the error sources are the same, and the limit to resolution is the minimum sample interval.

With digital expansion (in addition to the expansion achieved by increasing amplifier gain—which is a feature of both analog and digital scopes) and with the use of interpolators to fill in information between sample points, the limits of your timing measurements are extended. In practice, then, the errors in your timing measurements will be dependent on the number of samples taken of the input signal.

Timing measurement errors will also depend on the type of input signal and on the kind of interpolator used. Pulse-to-pulse timing and pulse width are examples of measurements for which a pulse interpolator works best. In these cases, the errors due to interpolation can be very small; for example, with three samples on the rise time of the input signals, an error of less than plus or minus 5% of the sample interval is present.

For a waveform displayed with 500 data points on the screen, this is plus or minus 0.01% of full scale.

For measurements like sine wave period and phase, a sine interpolator is best. In this case, at only 2.7 samples per cycle of the input signal, the timing error introduced by the interpolator is less than plus or minus 0.5% of the sample interval—plus or minus 0.001% of full scale with 500 data points.

These errors are shown plotted against the number of sampled points in Figures 34 and 35. The error curves demonstrate that errors due to interpolation will probably not be the limiting factors in your measurements; they are usually smaller than the errors caused by noise.

Vertical Accuracy

When stated individually, some accuracy specifications look pretty impressive to the unsuspecting user.

However, further investigation is necessary. Four major contributors to short term vertical error are amplifier gain, the A/D resolution, linearity and noise.

Gain accuracy is often stated simply as "accuracy." This is actually the dc error in the amplifier's gain, similar to that encountered with conventional scopes. This is often expressed as "% of F.S." (percent of full scale).

Resolution, as mentioned earlier, is the number of discrete levels which are available to represent the input signal. But when the actual signal level lies between the available levels, a quantizing error of $+\frac{1}{2}$ LSB (least significant bit) is inherent. See Figure 37.

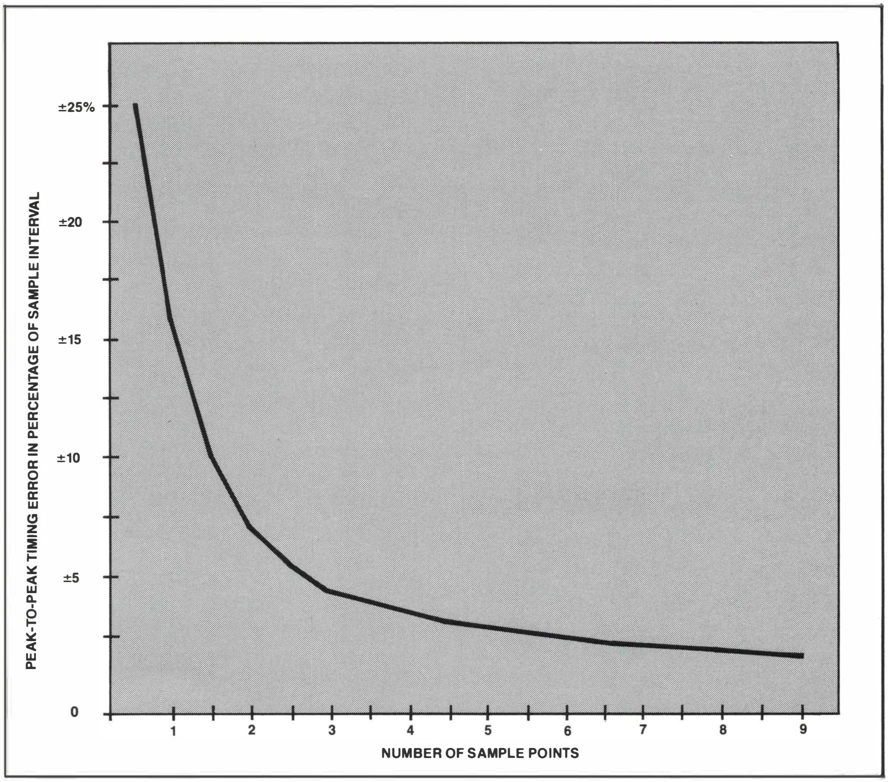


Figure 34. The errors introduced when measuring pulses with a pulse interpolator are shown above. The errors are plotted as measured from the 50% point of one waveform to the same point of another. To keep the results independent of the scope's digitizing rate, the error is reported as a percentage of the sample interval.

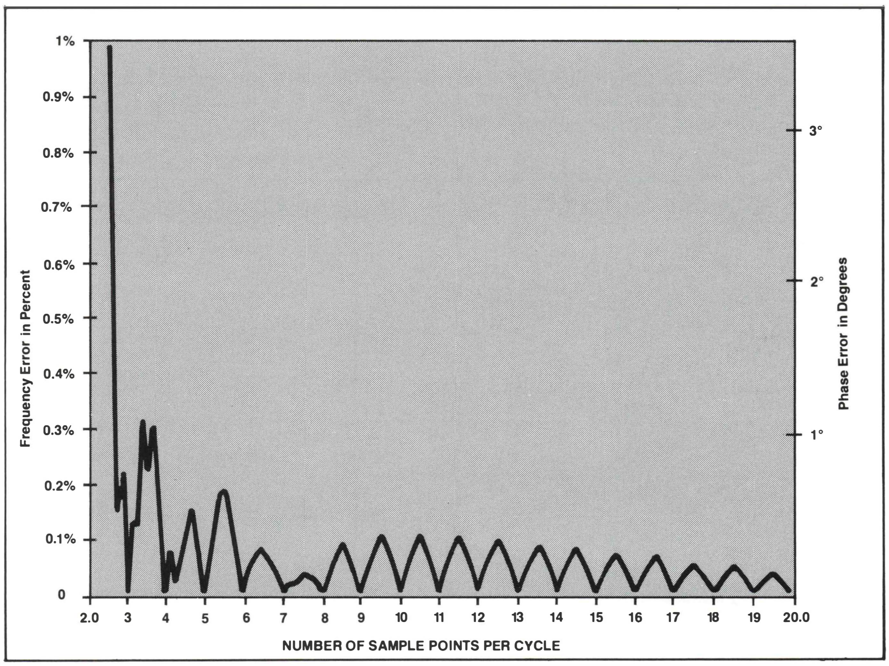


Figure 35. The maximum error introduced in frequency and phase measurements by the sine wave interpolator in the Tek 468 is plotted above. The error curve shown is for a single sine wave cycle.

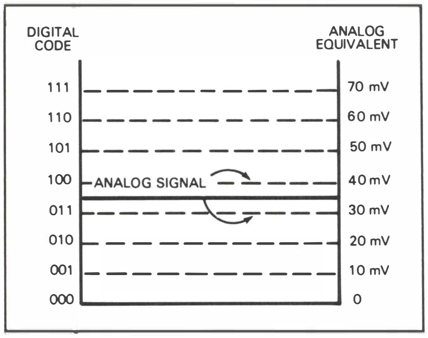


Figure 37. A perfect A/D converter exhibits +½ LSB quantizing error. For example, if each increment (or LSB value) is 10 mV/bit, a 35 mV signal cannot be truly represented. It will either be represented as 40 mV or 30 mV, which is an error of +5 mV or +½ LSB.

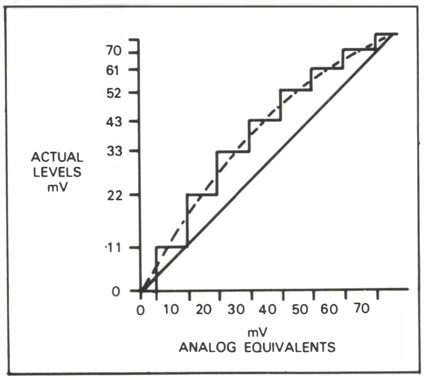


Figure 38. In reality, A/D and D/A converters do not have equal analog increments for each level. The analog equivalent may be, for example, (10 mV + 2 mV)/bit. The +2 mV is due to the device's non-linearity. So, for example, an input of 30 mV can only be represented as 31 mV—an error of 3.3%.

Linearity of the system is the incremental percent difference between discrete levels of LSB steps. See Figure 38.

Noise is usually presented in terms of rms. However, the peak-to-peak value is typically 4 to 5 times greater than the given rms value.

Consider the specifications of two different manufacturers shown in Figure 39.

The first set of specs state the accuracy as +3% for the vertical and horizontal.

Remember that, as with conventional scopes, this refers to dc gain accuracy. For this instrument, this is all that the manufacturer presented. This falls in line with the traditional specs for conventional scopes and is easily understood.

The other set of specs is not so general or easily discernible. But what the specs guarantee is largely signal dependent and expressed as a percentage of full scale. Here the user must be prepared to anticipate what sort of signal amplitude will be encountered. Also, the specs presented may only refer to the A/D section only, which means that the attenuators and display section are still unaccounted for. So, an example calculation must be made.

Given:

Accuracy	=	+0.25% of F.S.
Resolution	=	+0.025% of F.S.
Linearity	=	+0.1%
Noise	=	+0.02% of F.S. rms.

For a 2 volt dc signal displayed at 1 volt/div., what % error should be expected?

F.S. (full scale) = 10 DIV. x 1 V/DIV. = 10 V
Voltage Error (+) = 0.0025 x 10 V + 0.00025 x 10 V + 0.001 x 2 V + 0.0002 x 4 x 10 V
= +37.5 mV

$$\frac{\%\ \text{Error} = \text{Voltage Error} \times 100}{\text{Input Voltage}} = \frac{+0.0375\ \text{V} \times 100}{2\ \text{V}} = +1.875\% = +2\%$$

However, for a 5 volt signal, the % error is less than +1% with a voltage error of about 40 mV. Another interesting spec listed for this scope is the rise time spec. This is not simply the step response of the system. As stated here, this actually refers to the sampler's acquisition time. The 500 ns is the RC time constant of the sampler's storage capacitor. It takes 500 ns for the sampled signal to be at 67% of the input level, whereas at 2 ms (4 time constants), the sampled signal will be at 98% of the input level. So at the faster sample rates, additional amplitude error will be introduced. Again, depending upon the application, you must examine the instrument specs closely to determine if the instrument will indeed meet your requirements.

Figure 39 shows specifications for two digital storage scopes. On the left, accuracy is stated as an inclusive spec, whereas on the right the accuracy spec is presented as individual components and must be summed up.

Specification

Display
8 x 10 cm rectangular CRT operating at 4 kV
Illuminated Graticule

Vertical Deflection
Two identical input channels

Bandwidth: DC-10 MHz (±3 dB) in the Normal mode

Sensitivity: 5 mV/cm to 20 V/cm in 12 ranges
Uncalibrated fine gain control gives between range sensitivity adjustment.

Accuracy: ±3% in calibrated positions.

Input Impedance: 1 MΩ/28 pF

Input Coupling: AC-GND-DC

Maximum Input: 400 V DC or pk AC

Horizontal Deflection
Timebase: 1 µs/cm to 20 sec/cm in 23 ranges.

Accuracy: ±3%

X Expansion: Continuously variable from 1X to 10X with calibrated stops at each end.

Voltage

Resolution	0.025% of full scale.
Accuracy	±0.25% of full scale or better.
Linearity	Within 0.1% of best straight line or better.
Drift	0.05% of full scale per °C.
Noise	0.02% of full scale rms. 0.1 to 10^6Hz.
Input Impedance	50 pF in parallel with 1 mΩ.
Common Mode Rejection	10.000:1. dc to 10 kHz. 1.000:1. 1 kHz to 100 kHz.
CMR Range	±4 volts or ±10 times full scale, whichever is greatest, but not exceeding ±100 volts.
Voltage Limits	±100 times full scale, dc, and not exceeding ±200 volts, peak.
Rise Time	500 ns. 67%.
Sample and Hold Aperture Uncertainty	5 ns.
DC Offset	100% of full scale.
Scale Ranges	±100 millivolts, ±1 volt, and ±10 volts and x2, and x4 multiples of these.

Sweep and Timing

Sweep Timing Accuracy	±0.02% with an additional sweep start uncertainty of 25 nanoseconds. In the mode called "cursor trigger" used for observing pre-trigger information, a sweep timing uncertainty of one unit is additionally involved. One unit is the selected sweep time per point.
Sweep Time Range	From 500 nanoseconds per point to 200 seconds per point, in 1, 2, 5 and factor of 10 steps.

Figure 39.

Effective Bits

Effective bits is a measurement of the ability of a digitizing system to acquire a waveform and represent it accurately with numbers.

The measure of accuracy used is RMS (root mean square) error. This is the square root of the sum of all the squared errors for a waveform.

The measurement is made using a high quality signal source (usually a sine wave). The signal is digitized, and the error is calculated on the assumption that the signal was a high quality shape of unknown amplitude, offset and phase. Specifically, the RMS error is calculated as:

$$RMS_e = \sqrt{(\Sigma(WA_i - WI_i))^2}$$

Where:
RMS_e = RMS error
WA = Acquired waveforms
WI = Ideal waveform
i = Each point in the record

The ideal waveform is chosen so as to produce the lowest RMS error.

The RMS error of the acquired waveform is compared to the expected RMS error. There is an expected RMS error because the digitizer has some number of bits of resolution to which it is limited.

$$RMS_{ee} = \sqrt{(\Sigma(WID_i - WI))^2}$$

Where:
RMS_{ee} = Expected RMS error
WID = Ideal digitizer waveform

A bit is said to be lost each time the expected RMS error must be doubled in order to make it equal to the actual RMS error. Thus, "lost bits" is calculated as:

$$LB = \text{Log}_2(RMS_e/RMS_{ee})$$

Where:
LB = Lost bits
Log_2 = Log Base 2

Effective bits is calculated finally as the difference between the number of bits in the digitizer and the "lost bits":

$$EB = DB - LB$$

Where:
EB = Effective bits
DB = Digitizer bits

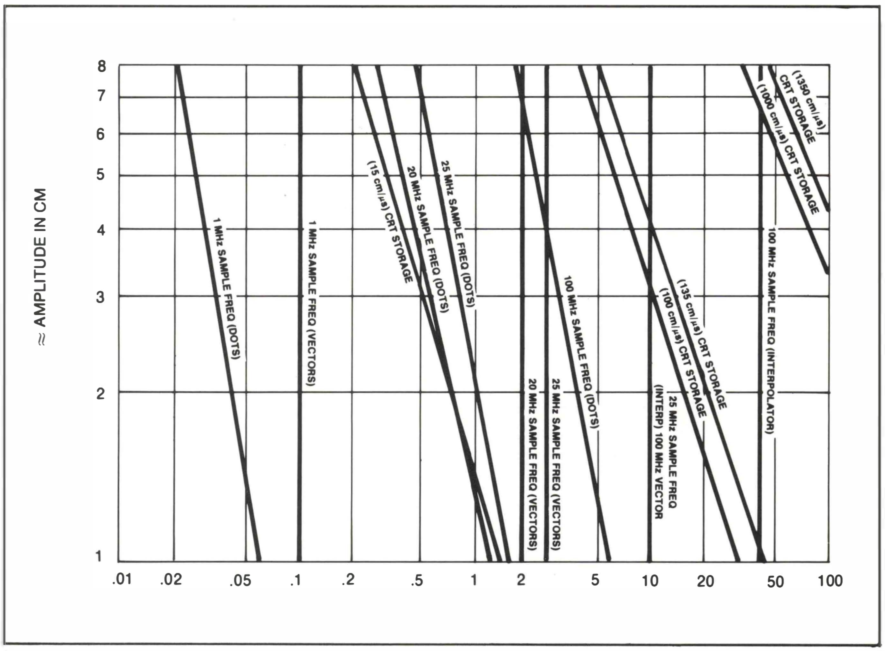


Figure 40. The single shot performance for the conventional CRT storage is based on stored writing rate. For digital storage, the curves are based on the maximum frequency displayable without causing perceptual aliasing.

Notice that the source of the errors is completely ignored by this calculation. The errors may be amplitude errors, as produced by a nonlinear amplifier. Or the errors may be errors of sampling time, meaning that the sample correctly represents the time at which it was taken, but was taken at the wrong time.

Thus, this measurement is of many factors that affect the ability of the digitizer to accurately represent a shape. The digitizer may have very high resolution, but lose effective bits because of accuracy errors. This is one more matter to consider in the purchase of your DSO.

Single-Shot Performance

Many digital storage scopes replace the need for conventional CRT storage for low frequency applications. In general, digital storage has not yet surpassed the single-shot performance of conventional CRT storage (scan converters are an exception).

For example, the R7912 has the equivalent sample frequency of 100 GHz, which results in a useful bandwidth of 10 GHz.

The rules of thumb given above for determining useful bandwidth can be derived theoretically (taking into account the display amplitude). A bandwidth comparison between conventional storage scopes and digital scopes using sine waves is shown in Figure 40. This comparison graphically demonstrates how the useful bandwidth of digital scopes is far surpassed by CRT storage scopes. And it may be some time before A/D conversion techniques catch up and are financially attractive.

INTERFACING TECHNIQUES

CAMAC

AKA: AEC-NIM CAMAC; IEEE Standards 583, 595 and 596; IEC Standard 516.

COMMENTS: Process I/O interface method which connects instrument modules to a computer. 24 bits of data are transferred in either parallel or serial. CAMAC defines hardware and protocol specifications for devices that are housed in CAMAC crates. Up to 62 crates, each containing up to 25 devices, can be connected by a CAMAC highway.

GPIB

AKA: General Purpose Interface Bus; HP-bus®; HP ASCII® bus; IEEE Standard 488; IEEE Standard Digital Interface for Programmable Instrumentation; ANSI Standard MC1.1.

COMMENTS: Process I/O interface which connects instruments to a computer or calculator. 8 bits of data are transmitted in byte serial over a 16-wire cable at distances up to 20 m. A single GPIB loop can contain 15 devices, one of which must act as a controller.

Serial ASCII

AKA: Teletype compatible, teletype interface, ASCII interface, ASCII bus.

COMMENTS: Once a de facto universal interface, serial ASCII is commonly used for connecting computers to peripherals and remote multiplexers. A serial ASCII data stream can be transmitted with RS-232-C devices or directly cabled with current-loop or voltage-loop techniques. Although some manufacturers have offered process I/O devices with this interface (notably Taylor) it is not in general use for process I/O.

Parallel Binary

AKA: Parallel interface, parallel bus.

COMMENTS: Connecting a process device directly to a computer and transmitting data in parallel mode is thought by many engineers to be the only acceptable interface methods.

RS-232-C

AKA: CCITT V.24, EIA RS 232

COMMENTS: An international standard which defines the manner in which serial data equipment is interfaced to modems. The standard defines signal functions, signal characteristics, cable length and pin assignments for standard 25-pin connectors. RS-232-C does not deal with the connection of process I/O devices to a computer.

The Tek 2220 and 2230 have a GPIB or RS-232-C as an optional feature. The 2430 comes standard with the GPIB interface.

HP-bus and HP ASCII bus are registered trademarks of Hewlett-Packard, Inc.

APPLICATIONS

Digital technology in a storage scope offers abundant advantages. Compared to analog storage instruments, digital scopes are easier to use and have more capabilities. You don't need interactive controls to store a waveform; storage takes place in a digital memory, not in the CRT. Digital storage scopes also offer features unavailable elsewhere. These inlcude pre-trigger viewing, automatic babysitting operations, digital data output and signal processing.

This section contains a description of how to use digital scopes, plus several examples of how to apply their features to your measurement needs.

Ease of Use

As with any storage scope, when using a digital storage scope, you are either "storing" and viewing waveforms as they occur, or you are "saving" them for further examination. In both cases, the digital storage scope substitutes push button controls for the several interactive potentiometers of other storage scopes.

Digital storage oscilloscopes may have two or more channels of data acquisition and a time base that behaves just like the non-storage scopes you are used to. Some will have delayed sweep capabilities or plug-ins you can use to adapt the instrument to your measurement needs. Generally, if you know how to use a non-storage oscilloscope, you will be able to operate a Tektronix digital storage scope with little, if any, additional effort.

Display flexibility also contributes to ease of use in digital storage scopes. With a direct view storage tube, once you have stored a waveform, you cannot change it. There is no way to reposition or expand a stored trace with scopes like these. However, you can do both with digital storage scopes. The number of traces you can store and recall depends on the scope's memory size and how many data words are used to represent the signal.

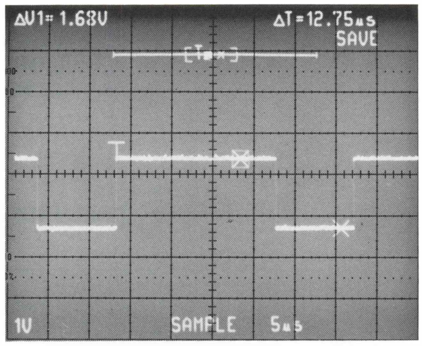


Figure 41. Digital storage scope advantages include the ability to make cursor measurements like the one shown above, using the Tek 2230. In the example, the CRT readout shows the time between two cursors on the screen. The time shown is adjusted automatically for the TIME/DIV. setting of the instrument. With this particular instrument, the cursors can also be used for voltage measurements. Character generation is another advantage of using some digital storage oscilloscopes. In the photo above, the voltage difference and intervening time between two cursors on the waveform along with scale factors for the time/div. and volts/div. switches are displayed.

Another display feature made possible by digital storage is shown in Figure 41 using the Tek 2230. The two Xs on the waveform are cursors that may be set by the user. The CRT readout (see locator arrows) above the display shows time and voltage between the two cursors. The CRT readout reduces misinterpretations by an operator. Coupled with expansion, the cursors improve repeatability of your measurements.

Roll Mode

Some digital scopes, such as the Tek 2220, 2230 and 2430, offer a display feature called "roll mode;" in this mode, new information is acquired by the scope and used to constantly update the screen. The effect is like looking at a strip chart recorder.

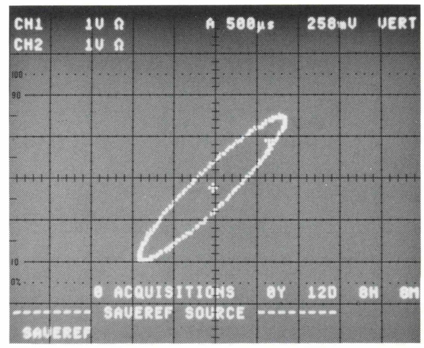


Figure 42. The display above shows two 150 MHz sinewaves 40 degrees out of phase. This is possible on the Tek 2430 because the scope has the ability to store a repetitive signal to this BW, and any signal that can be stored can be displayed in the X-Y format.

X-Y Display

If you need to make measurements with a B-H magnetization curve, draw pressure volume diagrams for an engine, or any other X-Y display, the X-Y display mode of a digital storage scope can be of benefit. Unlike most analog scopes, you will have two full bandwidth channels with a good phase relationship (figure 42) because in a digital storage scope there are no delay lines and you are not limited by the bandwidth of the horizontal amplifier.

Finding Out What Happened Before The Trigger

You set a trigger on a digital storage scope just like you do with any scope: you pick a slope and a level. But the time relationship between that trigger point and the information stored and displayed by the scope is more flexible than with analog scopes. With digital scopes, the point at which the trigger occurred doesn't have to be the first thing you see on the screen; data can be stored in any proportion before and after the trigger point. If you are operating the scope so that the display begins before the trigger point, you have selected pre-trigger viewing and you can see what happened to the signal before the trigger occurred.

Pre-trigger viewing is possible because a digital storage scope is constantly translating the voltage at the probe tip at the digitizing rate you selected. The trigger need not start the recording; it is only a reference point.

Pre-trigger viewing can be the only way to solve some problems—for example, a power supply problem in a computer. Triggering on the console warning light without pre-trigger viewing only lets you see what happened after the crisis, not what caused it. See Figure 43.

Pre-trigger viewing is of benefit anytime you want to find out what led up to an event, its being the only thing you have to trigger on.

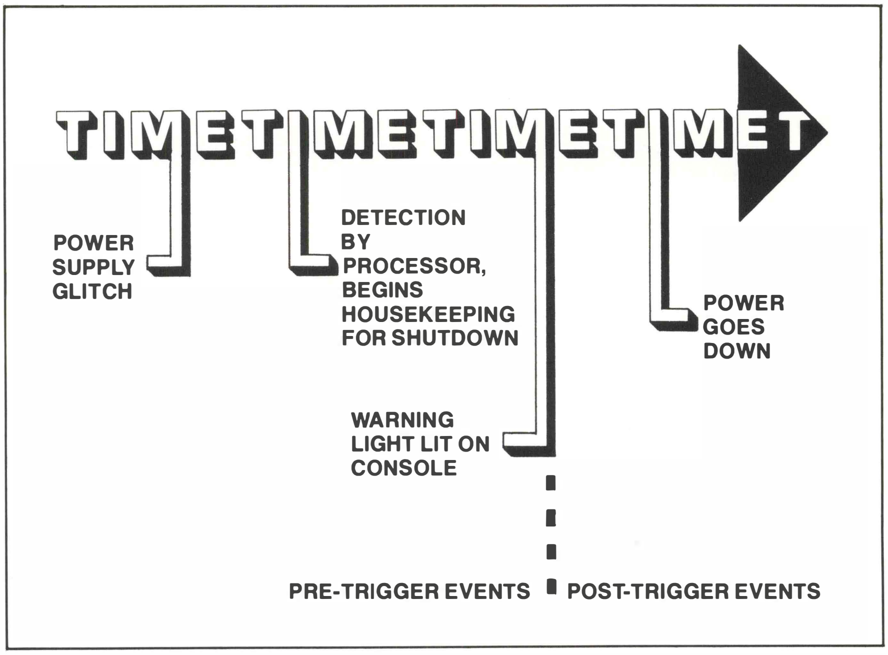


Figure 43. Computers and other "intelligent" machinery contain logic that monitors the power. If one of these circuits detects a problem, the central processing unit interrupts everything else and begins a power-down sequence that saves important data and prevents permanent damage. If you can only look at events after the power-down routine, the task of finding the cause of the failure is much more difficult. With pre-trigger viewing features, the digital storage scope allows you to find out what happened before the crisis, not just afterward.

Babysitting Your Problems

Suppose that while you are looking for a power supply problem you get a call that another of your machines is down.

Of course, you can't be in two places at once, but you can leave your digital scope in the single-sweep mode and go on your second call. When you get back, if a trigger has occurred, your scope will have automatically captured the data you need. The information will be stored in the digital memory; it won't have faded from the screen or been lost to an erase cycle.

This babysitting mode is based on the scope's triggering at an event you want to capture, not on a timer or a counter. Either post- or pre-trigger viewing is possible with babysitting by trigger event. Once you have set up the scope, you don't have to touch the controls again; you can go elsewhere and let the automatic feature take over.

Almost any digital storage scope can babysit for you this way, but some have another automatic mode. Remember the peak detect (envelope) mode described earlier as an anti-aliasing feature? With it, a scope such as the Tek 2230 or 2430 captures many examples of a repeating signal and saves all the minimum and maximum values of the waveform. To make the peak detect mode a babysitter, simply decide for how long you want the scope to run in this manner and then you can see how much noise there is on a data line. Or, you can monitor a line printer that occasionally drops bits. In these situations you would hook up your digital storage scope and leave it running—unattended, of course—for as long as necessary. When you get back, you can see if, and by how much, the signals exceeded the specifications. The display might look like that pictured in Figure 44.

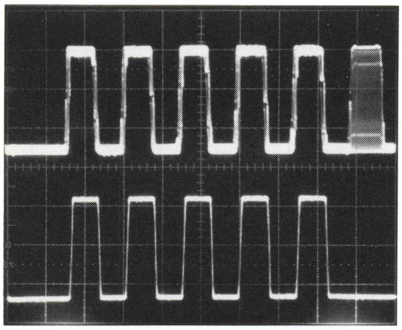


Figure 44. The envelope mode display of a digital storage scope is shown above. The variations about each pulse are a result of noise in the signal. The filled-in pulse is either a pulse that was missing in one of the sweeps, or it represents the opposite—one that appeared and should never have been there. The envelope mode is one form of babysitting; it captures the minimum and maximum voltage excursions of a signal over a specified time frame.

You can use the envelope mode to hunt for fast spikes on slow signals, or to watch any amplitude or frequency variations of a signal—all automatically.

As we mentioned earlier, with the 2430 you can even set envelope limits and capture any waveform that goes outside that limit.

Catching Glitches

Glitches are exasperating creatures. Sometimes they're there; sometimes they're not. This disappearing act makes them hard to catch, particularly if you're hunting for a glitch in some digital product. Glitches by nature are fast, and the waveform you want to see might require a TIME/DIV. setting that won't show the glitch even when it's there. The envelope mode is useful here—as well as for babysitting and for detecting aliasing—because it offers you dual digitizing rates. One, selected by the TIME/DIV. switch, lets you get the complete picture on the screen; the faster envelope mode rate will catch the shorter duration signal variations you would otherwise miss as long as they last longer than the envelope mode's minimum sample interval. In the 2430 the glitch capture is not limited by the digitizing rate because it uses an analog peak detector to give you the ability to capture a *2ns spike at any sweep speed.* Try that on any CRT storage scope!!!!

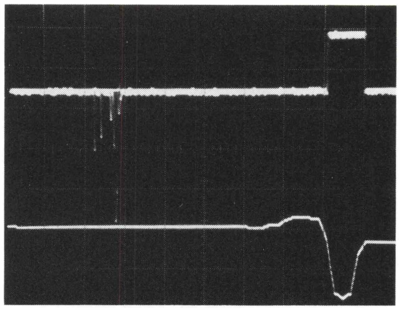


Figure 45. One of the uses of the envelope mode is as a glitch-catcher. The mode allows you to select the TIME/DIV. switch setting that gives you all of the signal you want to see while the envelope mode display is built from data captured at a much faster digitizing rate. For example, the photo above shows the effect of arcing on the grid drive waveform of a CRT. The envelope mode acquisition (bottom trace on the photo) was triggered on a blanking pulse while the digital scope's settings were 20 v/DIV. and 50 ms/div. The single sweep acquisition captured the normal operation of the blanking pulse and the abnormal arcing that occurred 0.25 seconds after the CRT was intensified. That trace was saved as a reference waveform and another acquisition (top trace) was taken to show the spike captured at 50v/DIV. and 200 ns/div.

Glitch-catching isn't the only time two digitizing rates are of help. High-voltage arcing in an x-ray tube is another example. Compared to the x-ray exposure times (from milliseconds to several seconds), the arcing is much faster and won't be captured without the faster envelope mode digitizing. As shown in Figure 45.

Keeping Records

Because the data captured by a digital storage scope is available as binary data words in the scope's memory, it is easily transmitted and recorded. If the reasons you use a storage instrument include making permanent records, you can take advantage of the data output features of some digital scopes.

The data can be transmitted to a central computer system for further processing, sent to an X-Y recorder for hard copies, or simply and permanently stored on tape or disc units for later display. Data logging can be the core of an automatic documentation process for your work.

It is important to know whether the data output from the scope is compatible with your other equipment. GPIB (IEEE 488-1975 General Purpose Interface Bus) or RS-232-C standards specify little more than pin locations and voltage levels. You should also determine if the data itself is formatted to a standard, as it is for all Tektronix digital storage instruments. Some digital scopes vary in data format even within products from the same company.

The Advantages

We can see that digital storage has some tremendous advantages with:

Ease of use. If you have ever tried to use a conventional variable or fast transfer storage scope, you will certainly see an improvement with most DSOs.

Trace Quality. Because there is no blooming and the trace is always of the same intensity, we have a significant improvement in trace quality.

Cursor measurement adds to DSO advantages with the ability cursors to add repeatability, accuracy and speed to measurements.

Averaging enables you to pick even small signals from noisy environments.

Resolution in the horizontal axis is much improved on most DSOs and, in many cases, so is the vertical.

The list continues with Pre/Post Trigger, interfacing to other devices via GPIB or RS232, processing capabilities and many other advantages.

So then, why not just digital storage exclusively—and no CRT storage?

The main advantage to CRT storage lies in single shot price/performance capability. We are still not at a point that makes A to D economically competitive, but the gap *is* narrowing.

SUMMARY

To summarize, there are many reasons why a digital storage scope is easy to use, including:

- push button storage controls
- expansion and repositioning of stored waveforms
- cursor measurements
- character generation
- roll mode, and
- good phase relationship between channels.

Of course, not every digital scope will have all the features listed, but all should have a bright, crisp trace that won't fade. The trace on the crt of a digital storage scope will always be as bright as that on a non-storage scope—even if the signal you captured was a single-shot event. You will be able to use most digital storage scopes in almost any ambient light conditions, and the writing speed performance of a digital scope doesn't deteriorate with usage.

Comparing Digital and Analog Storage Instruments

Digital storage scopes store data in binary form which enables sampling and quantizing. As a consequence, digital storage scopes behave differently from analog scopes. The differences show up in the storage abilities of the two kinds of instruments, in what happens when you use them past their limits, and in the nature of the measurement errors you can encounter. Table 2 summarizes these differences briefly, and in the last chapter, we will return to these subjects and compare digital and analog instruments in greater detail.

Table 2. CRT and Digital Storage Comparisons

	CRT Storage	**Digital Storage**
Storage Ability	Trade-off between signal amplitude and maximum stored frequency	Maximum stored frequency is independent of amplitude
	Difficulty in writing fast/slow transitions without blooming	No blooming Envelope mode allows fast glitch-catching at any sweep speed
Bandwidth	Fixed, as determined by the amplifier response and/or writing speed	Variable, as determined by the digitizing rate selected with the TIME/ DIV. switch; or fixed, with the envelope mode
Performance Beyond Bandwidth	Bandlimiting rolls off amplitude; high slew rate transitions will not be written	Aliasing creates false signals; narrow pulses will not be stored
Resolution	Resolution is uniform: vertically, it is limited by spot profile; horizontally, by trace width	Quantized vertical resolution; horizontal resolution limited by memory size and display reconstruction type
Measurement Error	Error characteristics are independent of the input signal; rolloff due to bandlimiting, linearity, etc. can be measured and used to improve measurement accuracy	Error characteristics are dependent on the timing relationship between the input signal & sample clock; maximum errors are on the same order as analog systems, but the error characteristics do not allow their use to improve accuracy

Table 3 lists the features of digital storage scopes that you might find useful in your applications.

Table 3. Digital Storage Scope Features

Feature	**Operations**	**Applications**
Pre-Trigger	Data is stored constantly; trigger is only a reference point; it doesn't start the data acquisition	Look at events occurring before the trigger; useful when the trigger event occurs after the event(s) of interest
Babysitting (with trigger)	Trigger can stop or start single sweep acquisition	Unattended recording of signal occurrence of interest
Babysitting (with envelope mode)	Envelope mode saves minima & maxima of signals	Unattended recording of signal excursions (such as drift) over a selected time frame
Babysitting (save on Delta)	Preset envelope is used to set limits	Any signal outside of preset limit is saved
Babysitting (scan roll scan)	If there is no trigger, then the signal is rolled from the trigger point. Upon a trigger the roll is stopped and scan is started to fill memory.	You may continuously acquire data before and after the trigger point at slow sweep speeds
Glitch-Catching	Envelope mode detects variations wider than minimum digitizing interval	Capturing fast variations of slower signals
Record Keeping	Digital data in scope's memory can be output to other equipment	Any permanent record keeping, hard copies, further data processing
Signal Processing	Digital data in memory is available for computations	Output of waveform data after processing to the screen, or through the data output facilities; also allows more accurate measurements with averaging

GLOSSARY

Accuracy
Absolute accuracy error of a DAC is the difference between the analog output that is expected when a given digital code is applied and the output that is actually measured with that code applied to the converter.

For an ADC, the accuracy is the difference between the analog input theoretically required to produce a given digital output code and the analog input actually required to produce that code.

The overall accuracy is affected by quantizing, offset error, bandwidth, linearity, monotonicity, settling time and long-term drift.

Acquisition Time
This is the time elapsed between the sample of track command and the point at which the output tracks the input (see text for more information).

A/D (or ADC)
Analog-to-Digital Converter

Aliasing
When a signal is sampled at a rate less than twice per period of the highest frequency component, an effect known as "aliasing" occurs. This is due to undersampling where the sampled amplitude information takes on the characteristic of an "alias" waveform of a lower frequency.

Amplitude Uncertainty (or Amplitude Error)
This error is a function of the analog signal and the aperture uncertainty. This is expressed as:

$$\text{Delta V} = \frac{T_a \, dV}{dt}$$

Where Delta V is the amplitude uncertainty, Ta is the aperture uncertainty, and dV/dt is the rate at which the signal is changing at the instant of sampling.

Aperture Time Delay
This is the time elapsed between the hold command and the point at which the sampling switch is completely open.

Aperture Uncertainty (or Aperture Time)
This is the variation in aperture delay. It is the difference between the maximum and minimum aperture.

Bandwidth
The input buffer amplifier and digitizer circuitry in the ADC have a finite bandwidth. This limited frequency response may cause lengthening of rise times which shows up as an apparent time shift of the time of sampling.

D/A (or DAC)
Digital to Analog Converter

Equivalent-Time Bandwidth
The highest attainable bandwidth for repetitive signals being sampled is referred to as Equivalent-Time Bandwidth.

Equivalent-Time Sampling
For repetitive signals which require multiple sweeps, samples are taken at varying times during the different sweeps until the waveform memory is filled.

Glitches
When a major transition occurs in the input code to a DAC, the worst case being the switching of all bits (a transition at ½-scale), the analog output may momentarily slew away from the value represented by the new code. This produces a large transient spike referred to as a DAC glitch.

Linearity
Linearity error of a converter is the deviation of the analog values, in a plot of the measured conversion relationship, from a straight line. The straight line can be either a "best straight line," determined by manipulation of the gain and/or offset to equalize the positive and negative deviations, or it can be a straight line passing through the end points of the transfer characteristic after they have been calibrated. The latter is referred to as "end-point" non-linearity, a more conservative measure, and is much easier to verify in actual practice.

Long-Term Drift
This is due mainly to resistor and semiconductor aging and can affect all specifications except resolution and quantizing error.

Memory Size
This may be expressed in a number of ways. Digitizers which feature selectable memory management will typically let the user determine the desired points-per-waveform. Digitizers with fixed resolution typically will specify the number of points-per-waveform.

Monotonicity
The output of a monotonic ADC or DAC never decreases in response to an increasing input stimulus (and vice versa).

Nyquist Frequency
If a continuous bandwidth limited signal contains no frequency components higher than f_n, then the original signals can be completely recovered without distortion if sampled at a rate greater than 2 f_n samples per second. f_n is referred to as the Nyquist frequency.

Offset Error
The output voltage of a DAC with zero code input, or the required mean value of input voltage of an ADC to set zero code out.

Perceptual Aliasing
An optical illusion caused by the eye's inability to perceive the proper time order of the displayed data points. This occurs at frequencies much lower than a tenth of the sample frequency.

Quantizing Error
All analog values within a given quantum are represented by the same digital code, usually assigned to the midrange value. There is, therefore, an inherent quantization uncertainty of $\pm 1/2$ LSB.

Real-Time Sampling
For single-sweep acquisition, the signal must be sampled so that all data points are taken at equal increments of time, one immediately following the previous, until the end of sweep.

Record Length
This is generally defined as the number of samples that are acquired per waveform.

Resolution
"Nominal resolution" is the relative value of the LSB, or 2-n for binary n-bit converters. This may be expressed as 1 part in 2n, as a percentage of full scale, in parts per million, or simply by "n bits."

Sampling: Equivalent-Time
For repetitive signals which require multiple sweeps, samples are taken at varying times during the different sweeps until the waveform memory is filled.

Sampling: Real-Time
For single-sweep acquisition, the signal must be sampled so that all data points are taken at equal increments of time, one immediately following the previous, until the end of sweep.

Sample and Hold (S/H)
This is an acquisition technique in which a very short sample pulse is applied to the input when a new sample needs to be obtained at the output. A S/H is normally left in the hold condition.

Sample Rate
This is the actual frequency at which a sample of the analog signal is taken. This may be expressed in samples/second, or hertz. This is usually limited by the maximum conversion and setting time.

Sampling Theorem
If a continuous bandwidth limited signal contains no frequency components higher than f_n, then the original signals can be completely recovered without distortion if sampled at a rate greater than 2 f_n samples per second. f_n is referred to as the Nyquist frequency.

Setting Time
This is the time it takes for a DAC's output to settle for a full-scale code change, usually to within the analog equivalent of $\pm 1/2$ LSB.

Track and Hold (T/H)
The T/H technique is allowed to "track" the input signal for a period of time prior to initiating a "hold" command. During the track period, the output follows the input. The T/H is normally left in track.

Useful Bandwidth
The frequency limit at which, for most measurements, minimal error is encountered. The useful bandwidth is constrained by perceptual aliasing and envelope error.

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